Applicability of knowledge-based and fuzzy theory-oriented approaches to land suitability for upland rice and rubber, as compared to the farmers' perception. A case study of Lao PDR

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Applicability of knowledge-based and fuzzy theory-oriented approaches to land suitability for upland rice and rubber, as compared to the farmers' perception. A case study of Lao PDR

by

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Disclaimer

"Science is nothing but perception." Plato (428 BC-348 BC)

Abstract

Food security and extra income are among the main concerns of farmers in least developed countries such as Lao PDR. Around 80% of the population depends on agriculture as main source of subsistence, being rice the staple food and principal crop. The topography conditions and narrow valleys of the country compel the farmers to cultivate upland rice over paddy. In recent years, the interest of China in latex has encouraged Lao farmers to plant rubber, but there is a lack of knowledge about its requirements and processing. Given the importance of upland rainfed rice and the interest on rubber, in this research the suitability of these two crops has been assessed using three different approaches: first a knowledge-based suitability prepared by farmers, second a traditional Boolean suitability classification performed using the Automated Land Evaluation System ALES, and third a fuzzy-based evaluation. In the first approach the farmers created soil maps based on their experience, then determined suitable crops according to their soil units. In the Boolean approach, ALES employs the FAO framework for Land Evaluation (1976) that defines suitability classes from land qualities and land characteristics. For the fuzzy model, the same land qualities and land characteristics defined in the Boolean approach were used. Different fuzzy membership functions obtained from the literature were employed and the weights for each parameter were calculated according to an Analytic Hierarchy Process (APH) that relies on pairwise comparisons. Information retrieved from field surveys was an input to define the land qualities for the models, as a result fallow was one of the main parameters to be considered; then the Boolean and fuzzy models were run for three hypothetical fallow periods. The three different suitability visions were compared on a cell by cell basis. The results show that the in the Boolean model the best conditions for upland rainfed rice are given with no fallow (S2 for 61% of the study area), while for rubber are given for a medium fallow period (S1 for 21% of the study area). In contrast, the potential suitability under the Boolean model gives a 2.8% of the total study area as highly suitable for rice and 24% as highly suitable for rubber. The results with the fuzzy theory show 50% of the study area as highly suitable for upland rice and 24% as highly suitable for rubber. The comparison between the three approaches reveals a moderate agreement between the fuzzy and Boolean models that varies with the fallow period, being the best correlation for rubber under medium fallow period (54% agreement, *kappa* 0.38). The comparison with the farmers' suitability shows a better agreement for upland rice (38%) than for rubber (22%) but with an agreement given completely by chance (negative kappa values). It seems that the low agreements have to do with the lack of knowledge on rubber and in the traditional use given to the land. In this study it has been concluded that the inclusion of farmers' knowledge allows obtaining results that seem to correspond with the current conditions in the area.

Key words: suitability, feasibility, fuzzy, upland rice, rubber, Lao PDR.

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1. INTRODUCTION

Agriculture is important as a source of food and income, but how, where and when to cultivate are the main issues that farmers and land managers have to face day to day. In less developed countries, where lack of advanced technology and investment are the major of the problems for crop growing, the competition for arable land is high and vital for survival. According to the United Nations Development Programme UNDP (2004) Lao People's Democratic Republic, (Lao PDR or Laos) is one of the least developed countries in the world. Its location, in a mountainous area, restricts the cultivable areas. For Lao PDR agriculture is the main source of subsistence for around 80% of the population. The high pressure over natural resources has resulted in the destruction of forests and the introduction of new crops that are market-oriented (Mahanty 2006).

Poverty is aggravated in the northern provinces of Lao PDR due to the limited or lack of infrastructure, which restricts the access to markets and social services. In Lao PDR the percentage of people living below the poverty line is around 38.6% UNDP (2001). With these conditions, the need of land use planning is imperative as a tool for land managers and farmers to take decisions.

Due to the interest of China in rubber and sugar cane, farmers in Lao PDR have started to change their cultivations from subsistence to cash and market crops. The lack of experience about the requirements for these crops makes necessary the evaluation of their suitability but also their feasibility.

While paddy rice is cultivated in valleys and flooded areas, upland rice is cultivated in slopes in a traditional way, without fertilizers, irrigation or machinery. Lao farmers' obtain a yield every six months. Rubber is a tree planted along with other crops such as fruit trees or corn. The main product from rubber is latex, and it is required a tree at least 7 years old (more or less depending on the rubber species) to obtain the first yield (NAFRI 2005).

Another factor that may have been underestimated in Lao PDR uplands is the soil losses due to the harvesting and fallow periods. The topography is conformed by steep slopes that may aggravate the erosion and reduce the suitability of arable land.

Unfortunately, most of the land development plans are made without use of the farmers' perception and knowledge, which may not agree with what the local people desire. On the other hand, the farmers' perceptions may not be optimal for the land conditions. The purpose of this study is to break with this dichotomy, finding a land suitability classification that agrees with both people's perception and traditional land classification but that is also feasible.

1.1. Problem Description

Lao PDR farmers are interested on getting additional sources of income, and the main resource available is land. Neighbouring countries such as China have shown interest in rubber; for this reason the Lao government induced its plantation as part of a poverty reduction program and to stop the slashing and burning cultivations in mountainous areas. According to the National Agriculture and Forestry Research Institute NAFRI (2005), rubber trees in China will fell in the next ten years because of their age and a high demand of rubber suppliers will arise.

The main obstacles for rubber cultivation is that farmers lack of "funds labour and experience" so the first crops were cultivated in Luang Namtha Province by China who provided all the investment and work. In year 2003 around 335 ha of rubber plantation reached the tapping age in Luang Namtha (NAFRI, 2005). The relation cost-benefit and the potential profit of this crop have attracted many farmers who are shifting or planning to shift at least part of their traditional cultivations into rubber.

Given the interest and potential of this cultivation to reduce poverty, the Swedish International Development Cooperation Agency SIDA in cooperation with NAFRI and other national Lao agencies have carried out workshops on rubber development and have provided seedlings to farmers who meet certain criteria of plots location, soils, labour and expertise. But even without support, funds or experience, Lao farmers are investing work and money in rubber crops.

But if rubber is a potential source of cash, the main crop for Lao PDR population is rice, which constitutes their staple food. Because of Laos topography paddy fields are difficult to grow so farmers cultivate upland rice in the land available.

In the study area, located in the Phonexay District, few and general land evaluation for rubber has been carried out. Projects on land suitability have been done in the area for rice and other seasonal crops but based solely on physical parameters, and relevant factors that may affect the feasibility of growing a crop such as accessibility, workability, land degradation and fallow periods -that are quite important for the farmers- have not been considered.

Furthermore, the land evaluation assessment in Lao PDR -if any- has been based on crisp models that follow the traditional Boolean theory, which assumes distinct patterns between classes and assumes high accuracy in measurements and spatial references of the objects, while the soils and vegetation changes occur transitionally and their registration is not accurate (Hall *et al*, 1992). The application of fuzzy logic for land evaluation can allow the relaxation of these limiting factors (Burrough 1989).

1.2. Previous Studies in the Area

Due to the interest in developing the Phonexay Distric, some workshops, research and papers regarding agricultural improvement and related topics have been prepared for the area. The most relevant reports that have been used in this study are summarized next.

Nilsson and Svensson (2005) used Agro Ecological Zones to asses the suitability of banana and pineapple in the Phonexay Province. In their study socio-economical factors were considered but the farmers' perception was not incorporated in the model.

Douangsavanh *et al* (2006) classified the soils of four villages corresponding to the study area according to the indigenous knowledge of the communities and villagers.

NAFRI (2005) elaborated a "Report on rubber and sugarcane markets in Northern Laos", including prices, market, areas cultivated, yield and statistics of China's imports of rubber and related products.

In the same way, NAFRI (2004) prepared a "Report on Household Diagnostic Survey in Phonexay District". This document includes information about population, gender, labour, migration, agriculture, livestock and wealth categories for the villages in the study area.

NAFRI (2002) prepared reports "On Soil & Land Suitability" for each of the villages of the study area: Thapo, Nambo, Huayman and Houaymaha.

1.3. Objectives and Research Questions

1.3.1. General Objective

The main purpose of the study is to prepare land suitability evaluation maps for rubber and upland rice using fuzzy classification for a sub area of Phonxay District in Lao PDR. In the model non-physical factors and parameters related to farmers' perception will be included. The results will be compared to a crisp classification using the standard FAO framework for land evaluation (1978) that will include non-physical parameters as well. Both the Boolean and fuzzy model will be compared to suitability maps for rubber and upland rice prepared by the farmers to determine their agreement.

1.3.2. Specific Objectives

The secondary objectives aim for a participatory approach to implement the farmers' perceptions into the suitability models. These objectives are:

- To asses the results of FAO land classification for Phonxay District in Lao PDR at village scale
- To compare the results of FAO land classification for Phonxay District at village scale to fuzzy classification incorporating farmers' perception of suitability.

1.3.3. Research Questions

For this study three main research questions are considered:

1. What areas are suitable and feasible for rubber and upland rice cultivation?

2. Is there any difference between FAO land suitability evaluation and the maps where fuzzy classification has been applied? Which results seem to be more realistic?

3. Do the results obtained with FAO and fuzzy models correspond to the farmer's suitability maps?

Three additional questions related to the main research will be briefly discussed:

1. What is the minimum input data required to obtain reasonable results?
2. What is required to convert non-feasible cultivations into feasible ones?
4. Are land degradation aspects sufficiently considered?

1.4. Thesis Structure

Chapter 1 gives and introduction to the research topic and justifies the research. It includes a summary of previous works in the area and presents the research questions and the research design.

Chapter 2 provides a succinct description of different land evaluation methodologies. This chapter also presents the fuzzy logic theory and its applications in land evaluation.

Chapter 3 describes the study area. It includes a brief history of Lao PDR and its actual conditions. The chapter describes also the agricultural conditions in the four target villages of the research.

Chapter 4 introduces the methods and materials employed in the research for its three components: farmers perception maps, Boolean land evaluation using FAO framework (1978) and fuzzy modelling.

Chapter 5 presents and compares the results from the different land suitability results according to the methodology provided in Chapter 4.

Chapter 6 compiles the main conclusions and recommendations from the analysis done in Chapters 4 and 5 and in relation to the objectives and research questions.

2. LITERATURE REVIEW

2.1. Why Land Evaluation?

A farmer may be interested in how much yield he or she will obtain when cultivating banana in one of his or her plots; an agricultural organization may be interested in increase the living conditions of a village introducing cash crops; water and soil specialists may be interested in how the land will be degraded if used for rubber in a steep slope. These doubts can be solved by evaluating the conditions of the land for each of the proposed uses. In this chapter the meaning, objectives and main methodologies available for land evaluation are discussed.

2.1.1. Land Evaluation Defined

According to FAO (1983) land evaluation is "the process of assessment of land performance when used for specified purposes". In other words, Land Evaluation is the estimation of the possible behaviour of the land when used for a particular purpose; this use can be the current one or a potential one. In this sense, Land evaluation can be regarded as a tool to take decisions about the land.

2.1.2. Methodologies for Land Evaluation

Different methodologies have been developed for land evaluation. Some of these systems were developed before the FAO Framework for Land Evaluation (1978), such as the USDA Land Capability Classification (Klingebiel and Montgomery 1966), or the USBR Land Suitability for Irrigation (U.S. Department of the Interior 1951), (Rossiter 1994).. After the FAO Framework new land evaluation systems have been created, such as the Fertility Capability Soil Classification System (FCC) by Sánchez *et al* (1982), or the Land Evaluation and Site Assessment LESA developed by the U.S. Department of Agriculture (U.S. Department of Agriculture 1983). For regional, country or continental scales, FAO developed the Agro-Ecological Zones system FAO (1976).

The variability between land evaluation methodologies is given by the particular use to be considered, the parameters regarded as relevant for that use and the scale of analysis. For a large scale study, i.e. town or village level, Land Utilization Types can be more convenient, while for more general studies, i.e. province or country level, Agro Ecological Zones may be more appropriate.

a) USDA Land Capability Classification

In this classification the soils are grouped according to their capability for cultivation production. The classification defines three categorizes for the soils: capability unit, capability subclasses and capability classes.

The first category, capability unit, is a grouping of soil mapping units with similar potentials and limitations, thus with similar management requirements; the capability subclass is a group of capability units with similar limitations.

The capability classes are groups of subclasses with the same degree of limitations or hazards; the classes show how good a soil is for agriculture. The capability classes are given between I and VIII, being I a soil with few limitations restricting its use, and VIII a soil with limitations for commercial plant production (Klingebiel and Montgomery, 1966). This classification system is useful for broad soil classification and land management. Some of the constraints of this classification system are: it does not consider economical factors and does not evaluate the land for a particular use (Rossiter, 1994).

b) USBR Land Suitability for Irrigation

The main purpose of this system is to classify the land according to its potential under an agricultural program. Its basic principle is the separation of land that can be irrigated from those that can not and according to the land repayment analyses.

The suitability for irrigation is given by a classification, where Class 1 is land with high payment capacity, Class 5 are not suitable for irrigation but have potential value and Class 6 is land not suitable for irrigation. The factors considered for land classification include both economic (productive capacity, costs of production, land development) and physical (topography, slope, relief, drainage). (U.S. Department of the Interior 1951).

Similarly to the FAO classification, this system includes economic factors and divides the land according to its requirements, which are comparable to the Land Utilization Types of FAO (Rossiter, 1994).

c) Land Evaluation and Site Assessment LESA

LESA combines the relevant factors for agriculture use with soil qualities. The soil quality factors are grouped under Land Evaluation and the other under Site Assessment. The Site Assessment factors are of three types: non-soil but related to agricultural use, related to development, and other public values of the site (Pease J. and Coughlin R. E. 2001). The main aim of LESA is to identify land with the best productive value and economically viable as farmland.

d) Parametric Indexes

In this classification system, the land is evaluated according to numerical indexes that rate it from 0 to 100 (or from useless to good) based on land characteristics. The land characteristics can be multiplied or added, depending on the system. The Productivity Index (Nelson *et al.*, 1963, in Olson (1981)) is a multiplicative index that combines ratings assigned to soil map units and other physical conditions that affect the land use; while the point system is an additive classification that rates the factors with a portion of a high score, for example a portion of 100; each factor has a score that is added to asses the land suitability (Rossiter, 1994).

e) Fertility Capability Soil Classification

The Fertility Capability Soil Classification (FCC) groups soils according to the problems to manage their chemical and physical properties for a certain purpose. The classes created with the FCC indicate the soil constraints related to fertility that can be understood as land utilization types (Sanchez *et al*, 1982).

f) Agro Ecological Zones (FAO, 1996)

Agro Ecological Zones (AEZ) are subdivisions of an area of land into units with similar characteristics for crops production and environmental impact. The classification is done based on the soil, landforms and climatic characteristics. AEZ allows assessing land suitability and productivity (FAO, 1996).

The activities to obtain AEZ imply (FAO, 1996):

- Make an inventory of land utilization types and their requirements
- Define and map AEZ based on land resources such as climate, landform and soils
- Evaluate the suitability in each AEZ

The main elements to apply AEZ include (FAO, 1996):

- land resource inventory

- inventory of land utilization types and crop requirements
- land suitability evaluation, including:
- potential maximum yield calculation
- matching of constraints and requirements

According to FAO (1996) the inputs are scale independent, but the final map and the study objectives will determine the level of detail for soil, climate and land utilization types.

g) Framework for Land Evaluation (FAO, 1976)

In this study the FAO Framework for Land Evaluation (1976) has been employed to classify the potential land use. FAO establishes the five basic principles for any land evaluation as follows:

1. Land suitability has a meaning only in terms of a particular use. What is suitable for one type of cultivation may not be suitable for another.
2. The land use specified must have a sustainable basis.
3. Land evaluation involves the comparison of different potential uses.
4. Different land uses are compared on economic basis.
5. A multidisciplinary approach is adopted.

The Framework for Land Evaluation aims to determine Land Utilization Types (LUT) or potential uses for land areas. The LUTs are specified by Land Requirements or land conditions for a "successful and sustained practise" (FAO, 1983).

For each LUT the suitability has to be defined. Suitability is the adaptability of an area for certain land use (FAO, 1976): given different parameters a land unit can be highly suitable for coconuts but not suitable for tomatoes.

According to FAO framework for land evaluation, the structure for suitability classification is composed by four categories:

i. Land Suitability Orders: reflecting kinds of suitability. S: suitable, N: non suitable.

ii. Land Suitability Classes: reflecting degrees of suitability within Orders. For example S1, S2, S3 etc. The number represents the degree of suitability or non suitability, (S1 most suitable, N2 the permanently not suitable).

iii. Land Suitability Subclasses: reflecting kinds of limitation, or main kinds of improvement measures required, within Classes. S2m, S2e, etc.
iv. Land Suitability Units: reflecting minor differences in required management within Subclasses. S2e-1, S2e-2.
In this research, three suitability classes highly suitable S1, moderately suitable S2 and marginally suitable S3 and one not suitable class N were considered.

Table 2. 1. Categories for suitability (adapted from FAO, 1974).

ORDER	CLASS	SUBCLASS	UNIT
S Suitable	S1	S1m	S1-e1
	S2	S2e	S2-e2
	S3	S3me	S3me-3
	etc.	etc.	etc.
Phase:			
Sc Conditionally Suitable	Sc2	Sc2m	-
N Not Suitable	N1	N1m	
	N2	N2e	
		Etc.	

The land suitability classification can be qualitative of quantitative, depending on the use of numerical or categorical data. Furthermore, the classification can be current, for the actual state of the land, or potential for the conditions at a future state (for example after land irrigation).

Land suitability is determined by *land characteristics*, *land qualities* and a *diagnostic criterion*. Land characteristics are attributes of land that can be measured like slope angle, soil texture, biomass, etc. Land qualities are attributes that influence the suitability for a particular use positively or negatively, like moisture availability, erosion resistance, etc. Diagnostic criterion is a variable whit a specific influence in the inputs or outputs for certain use; there can be land characteristics or land qualities. Diagnosis criterion acts as a basis for assessing suitability.

In land classification, the final map is one of the main outputs but the information about utilization types and management specifications is also important. After the land suitability evaluation has been done, the decision about the use to be selected depends on physical and economical factors; in this way, perhaps the most suitable use will not be chosen due to its viability (FAO, 1976).

2.2. Fuzzy Modelling and its Applications for Land Evaluation

The traditional concept of modelling employs a Boolean approach: the value is true or false. This approach tends to represent reality in a discrete way. But what can be found in the nature is that few elements are discrete, they are rather continuous. In the real world, some objects are quite differentiated from others and their boundaries are quire evident: a river crossing through a valley is quite distinguishable from its surroundings when in full discharge, an area covered by a lake is distinct from the land areas surrounding it; but soil and vegetation and other patterns in nature change transitionally: the limit between two types of soil or vegetation is, in most of the cases, not so clearly defined. Fuzzy modelling appears as an alternative to deal with these continuous or uncertain environments. While in Boolean logic a value is true of false, with fuzzy logic the value could be partially false of partially true which allows for a representation more according to the reality.

2.2.1. Fuzzy Theory

Fuzzy logic was initially developed by Lofti Zadeh in 1965 as a generalization of classic logic. Zadeh (1965) defined a fuzzy set as "a class of objects with a continuum of grades of memberships"; being the membership a function that assigns to each object a grade ranging between zero and one, the higher the grade of membership the closest the class value to one.

Traditionally thematic maps are represented with discrete attributes based on Boolean memberships, such as polygons, lines and points. These types of entities have a value or do not have it; an intermediate option is not possible. With fuzzy theory, the spatial entities are associated with membership grades that indicate to which extent the entities belong to a class (Hall *et al*, 1992). Figure 2.1 presents a representation of traditional Boolean sets and fuzzy sets: while with Boolean logic the boundary between sets is clearly defined (A and B), with fuzzy logic there is a transition zone where each set has less membership grade in relation to the other. In fuzzy theory, the map for A shows membership values closer to 1 when the set falls within A category, while the values are close to 0 when they are far from the category; the same applies for category B.

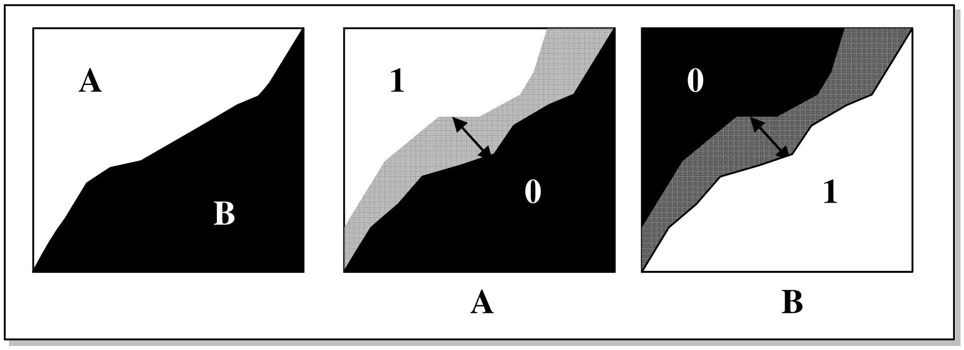


Figure 2. 1. Representation of crisp and fuzzy sets.

Mathematically, a fuzzy set can be defined as (McBratney A. B. and Odeh I. O. A. 1997):

$$\mathbf{A} = \{x, \mu_A(x)\} \text{ for each } x \in \mathbf{X}$$

Where μ_A is the function (membership function MF) that defines the grade of membership of x in A. The MF $\mu_A(x)$ takes values between and including 1 and 0 for all A. If X = $\{x_1, x_2, \ldots x_n\}$ the previous equation can be written as:

$$\mathbf{A} = x_1, \mu_A(x_1) + x_2, \mu_A(x_2) + \ldots + x_n, \mu_A(xn)$$

In plain words equations 1 and 2 mean that for every x that belongs to the set X, there is a membership function μ_A that describes how the degree of ownership of x in A is.

McBratney and Odeh (1997) expressed the fuzzy membership function as $\mu_A(x) \rightarrow [0,1]$ with each element x belonging to X with a grade of membership $\mu_A(x) \in [0,1]$. In this way $\mu_A(x) = 0$ represents that the value of x does not belong to A and $\mu_A(x) = 1$ means that the value belongs completely to A. Alternatively $0 < \mu_A(x) < 1$ implies that x belongs in a certain degree to A.

The membership function can take any shape and can be symmetrical or asymmetrical. The simplest function is of triangular form but trapezoidal, Gaussian, parabolic among others are also possible, as can be seen in Figure 2.2.

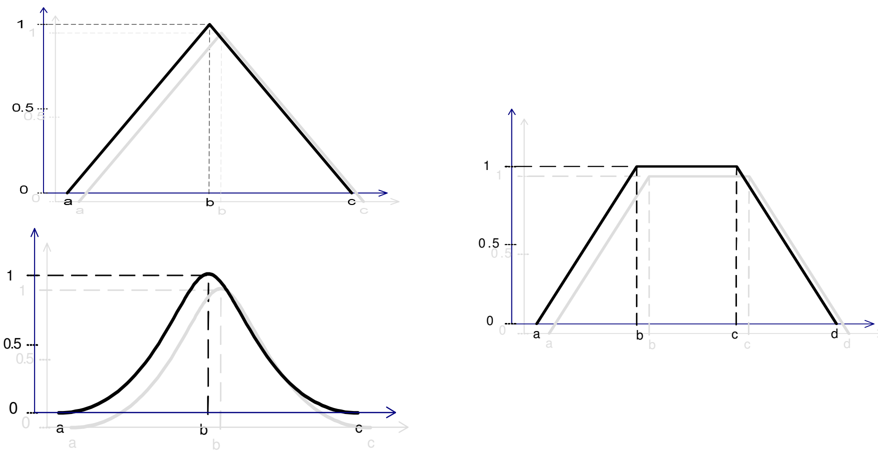


Figure 2. 2. Examples of membership functions (Adapted from McBratney and Odeh, 1997).

The basic operations that can be performed using fuzzy sets are a generalization of those that can be done with crisp sets (Zadeth, 1965). McBratney and Odeh (1997) present a summary for two fuzzy sets, **A** and **B**, belonging to finite sets **X** of real numbers $\Re$.

Inclusion: A is included in **B** if $\mu_A(x) \leq \mu_B(x)$, $x \in$ **X**, and denoted as $\mathbf{A} \subset \mathbf{B}$

Equality: **A** and **B** are equal if and only if $\mu_A(x) = \mu_B(x)$, $x \in$ **X**, and denoted as **A** = **B**. If one $x \in$ **X** does not satisfy the equality, then $\mathbf{A} \neq \mathbf{B}$

Complementation: **A** and **B** are complementary if $\mu_B(x) = 1 - \mu_A(x)$, $x \in$ **X**. This is denoted as $\mathbf{B} = \bar{\mathbf{A}}$, or $\bar{\mathbf{A}} = \mathbf{B}$. And the complement of **A** is **A**. The complement corresponds to the operator *NOT*.

Intersection: This is defined as the largest subset with elements from **A** and **B**, $\mathbf{A} \cap \mathbf{B}$, with $\mu_A \cap \mathbf{B}(x) = (\mu_A(x) \wedge \mu_B(x)) = \min(\mu_A(x), \mu_B(x))$, $x \in$ **X**. This operator is equivalent to AND operator.

Union: Defined as the smallest fuzzy set with elements from both A and B. This operator corresponds to the OR. $\mathbf{A} \cup \mathbf{B}$, is $\mu_A \mathrm{U}\, \mathbf{B}(x) = (\mu_A(x) \vee \mu_B(x)) = \max(\mu_A(x), \mu_B(x))$, $x \in$ **X**.

Product: The product of two fuzzy sets can be defined as

AB = μ_A $(\cdot)_B z = \vee (\mu_A(x) \wedge \mu_B(y)) = \max(\mu_A(x), \mu_B(x))$, x, y, z$\in$ **X**. Where z = x - y.

Fuzzy logic is also a generalization of Boolean logic that instead of using the binary TRUE and FALSE values applies "soft" variables such as deep, moderately deep, steep, etc. These variables are defined in an interval ranging between 0 and 1 allowing a continuous range of values (McBratney and Odeh, 1997).

2.2.2. Fuzzy Applications for Land Suitability

Given the non-discrete characteristics of soils and land use, fuzzy theory suits well to the analysis of land suitability. With fuzzy representation the boundaries between suitability classes are not so strict and map units that are more or less suitable -that is in an intermediate condition- can be described properly. The development of GIS has contributed to facilitate the mapping of land evaluation results, both Boolean and fuzzy, but the topological rules imbibed in GIS software are based on crisp theory.

Several successful research projects have been applied fuzzy modelling for land suitability. Some examples related to this work are presented next.

Application of fuzzy logic to land suitability for rubber production in peninsular Thailand (E. Van Ranst, H. Tang, R. Groenemans, S. Sinthurahat, 1996, Geodema 70 (1996) l-19)

Van Ranst *et al* (1996) employed fuzzy classification to determine the impact of land qualities on rubber production in Thailand. The total area covered by their study comprises 41 thousand squared kilometres. 28 land units spread in 5 areas were determined based on topography, climate and soil parameters. The land qualities that according to Sinthurahat (1992, referred by Van Rast *et al*) affect rubber production in Thailand and that were assessed by Van Rast *et al*, are "availability of nutrients, oxygen, water availability, temperature regime, workability and erodibility".

Van Ranst *et al* evaluated the land suitability using FAO framework for land evaluation. For each land quality membership functions were established based on FAO and rubber requirements. Membership functions specify the degree to which the value of a land quality belongs to a particular suitability class. Van Ranst *et al* used a S membership function because according to him "it gives the best results among the different shapes of membership functions". Van Ranst *et al* defined the memberships based on "expert judgement and experience".

With the land qualities per land unit allocated to suitability classes, a "characteristic matrix" (CR) was constructed. Because each land quality has a different influence on the land suitability, their influence on rubber production can be expressed in terms of a weigh factor, which will form a weight matrix (W). The final suitability classification is obtained multiplying the characteristic matrix by the weight matrix.

Van Ranst *et al* found a high correlation between fuzzy methodologies, multiple linear regression and the parametric approach. They concluded that the accuracy of the evaluation for rubber depends on the quality of the weighting of land qualities.

Fuzzy relational calculus in land evaluation
(R. Groenemans, E. Van Ranst, E. Kerre, 1997, Geoderma 77 (1997) 283-298)

Groenemans *et al* (1997) approach takes into account the relationship between land qualities $Q = \{q_l, q_2, \ldots, q_m\}$ and land units $U = \{u_l, u_2, \ldots, u_n\}$ to describe the suitability for a crop. The suitability relationship S assigns to each land unit u_i a land quality q_j using a Cartesian product $Q \times U$, "where (ui, qj) $\in$ S if in land unit u_i the quality q_j is suitable (S) for the crop considered and (ui, qj) $\notin$ S if in land unit u_i, land quality q_j is not suitable (N) for the crop considered".

Using relational calculus, a relationship between land units U to U is obtained if the land quality q_j exists in land units u_i and u_k. The same type of relation can be constructed between land qualities, Q to Q, meaning that for all land units u_i, if the land quality q_i, then the land quality q_j is also suitable.

Once the suitability values S_{ij} and the effective yield Y_i are known for each land unit, the latter can be rescaled to express if u_k is more suitable than u_i are according to the yield ($y_1 \rightarrow y_k$). Then, the least squares criterion is used to obtain the weights minimizing the differences between observed relationships ($y_1 \rightarrow y_k$). When the weights have been calculated, they can be used to forecast the yield in another land unit.

In the methodology presented by Groenemans *et al*, the land unit with the highest index is considered the most suitable for a certain crop. With fuzzy theory, these indexes are calculated based on two basic assumptions (Groenemans *et al*, 1997):
"(1) the more land qualities are suitable in a land unit, the higher the overall suitability of that unit;
(2) land qualities with larger weights are more important for the overall suitability than those with smaller weights".

Fuzzy modeling of farmers' knowledge for land suitability classification
(Rodrigo S. Sicat, Emmanuel John M. Carranza, Uday Bhaskar Nidumolu, Agricultural Systems 83 (2005) 49–75)

Sicat *et al* (2005) used fuzzy modelling incorporating the farmers' knowledge (FK) to assign the weights of the membership functions. The final objective was to make land suitability maps for agriculture in Nizamabad Distric of Andhra Pradesh State in India. Through interviews, local perception of cropping season, soil colour, soil texture, soil depth and slope were obtained to generate multi-class fuzzy sets using the S membership functions. From the interviews, 12 rules for land suitability classification were obtained. The farmers' classifications were compared to scientific descriptions, founding for all the parameters except color a good analogy. Because the FK is binary for color and crop season, binary fuzzy factors maps were generated. For these binary maps, fuzzy memberships between 0.05 and 0.95 were assigned instead of 0 and 1 because farmers are not absolutely certain about suitability or non suitability (Sicat 2005).

The factor weights were obtained assigning grades to the ranks of suitability for each factor. The grades per factor were added and the sums of grades per factor added again. The weight per factor was calculated by "dividing sum of grades per factor by sum of all grades". The obtained weight factor was multiplied to the corresponding fuzzy factor map, excluding the maps based on cropping season.

The results were compared to traditional land suitability maps to asses thee agreement. The percentage of agreement was calculated based on the number of cells that overlapped the fuzzy suitability maps and the traditional suitability maps. A percentage of agreement of 73% was found for the cropping season between July and October.

Cultivation Potential in Hambantota District, Sri Lanka. A Minor Field Study. Geobiosphere Science Centre (MSc thesis, Lund University. Per Schubert, 2004).

Schubert (2004) studied the cultivation potential for paddy and banana for Hambantota and Gampaha districts in Sri Lanka. Qualitative parameters obtained through interviews to stakeholders and quantitative parameters obtained through field measurements and recorded by FAO in the ECOCROP database (http://ecocrop.fao.org/) were considered to evaluate the suitability. The quantitative parameters include soil fertility, drainage, texture, depth and pH.

Schubert used the FAO framework for land evaluation (FAO, 1976). Five main soil groups were classified according to their suitability, and three suitability classes were employed: highly suitable (S1), suitable (S2) and non-suitable (N). For the fuzzy memberships, a Semantic Import Model (SI) was applied. The membership weights were obtained using a general membership function, given by the following equation:

$$\mu_A(x) = \frac{a}{1 + a(x - c)^2} \qquad \mathbf{x \geq 0} \qquad \mathbf{x \in X}$$

In the equation, *a* is a parameter that controls the shape of the function and the position of the cross-over points while the expression $(x\text{-}c)^2$ controls the dispersion. Schubert states that this equation, given by Burroughs (1986) is "commonly used when an a priori membership function is derived".

Comparison of Boolean and fuzzy classification methods in land suitability analysis by using geographical information systems (Hall G.B, Wang F, Subaryono J. Environment and Planning A, 1992, volume 24, pages 497-516).

Hall *et al* (1992) prepared a land suitability evaluation for the Cimanuk watershed, located in northwest Java, Indonesia. The purpose of their study was to asses the performance of Boolean classification methods such as FAO framework for land evaluation versus a fuzzy classification methodology.

For the fuzzy evaluation the coverages representing different land characteristics were overlaid to create a composite map that can be considered a vector in an m-dimensional space:

$\bar{q} = (a_1, a_2, \ldots, a_m)$ where a_i $(1 \le i \le m)$ is the i^{th} land characteristic. The vector $\bar{q}$ is called by Hall *et al* an area vector. In land suitability the areas have to be classified into S1, S2, S3 and N depending on their land characteristics. Hall *et al* used the distance between an area vector and a class to measure the similarity. If the class is represented as another vector $\bar{\mu}_i$:

$\bar{\mu}_i = (\mu_1, \mu_2, \ldots, \mu_{im})^T$ $(1 \le i \le 4)$, where m is the number of physiographic characteristics,

Then the Euclidean distance between $\bar{q}$ and $\bar{\mu}_j$ is:

$$d_E(\bar{q}, \bar{\mu}_j) = \left[(\bar{q} - \bar{\mu}_j)^T \cdot (\bar{q} - \bar{\mu}_j) \right]^{\frac{1}{2}}$$

This distance represents how similar is the area vector to a class *c*. With a small distance the similarity between $\bar{q}$ and *c* is bigger. The membership function f_c for a class *c* was defined by Hall *et al* as:

$$f_c(\bar{q}) = \frac{1}{d_E(\bar{q}, \bar{\mu}_j)} \Bigg/ \sum_{i=1}^{p} \frac{1}{d_E(\bar{q}, \bar{\mu}_j)}$$ where p is the number of classes.

The summation in the denominator is a normalizing factor, and $f_c(\bar{q})$ is the grade of membership of the area $\bar{q}$ in the suitability class *c*.

If $d_E(\bar{q}, \bar{\mu}_j) = 0$, the membership grade is equal to 1 for that class and 0 for the others.

In their study it was found that the assignment of suitability orders with the Boolean theory (that is, S1 for suitable, S2 for less suitable, N for non-suitable and so on) restricts the results for available land for a potential use: large areas of the study areas were classified with the same rating while for the fuzzy classification a higher variation of suitability were found. According to Hall *et al*, these results are a consequence of the matching between suitability-class requirements and land characteristics, where the land is a member of the suitability class or is not and no intermediate values are possible. In this study it is concluded that fuzzy processing allows obtaining information about the degree of land suitability class, which is relevant for land use planers to know how highly or moderately suitable is the land for a crop.

3. STUDY AREA

The study has been carried out for a group of villages (*Kum Ban*) located in the District of Phonexay, in the Province of Luang Prabang. The total number of villages in the area is six, but administratively they have been categorized in four: Thapo (conformed by Thapotai and Thaponeua), Nambo, Houayman and Houaymaha (conformed by Houaymaha and Poungpao). To understand the current conditions of Laos PDR it is necessary to take a look into its history and current conditions. Figure 3.1 shows Lao PDR and the study area.

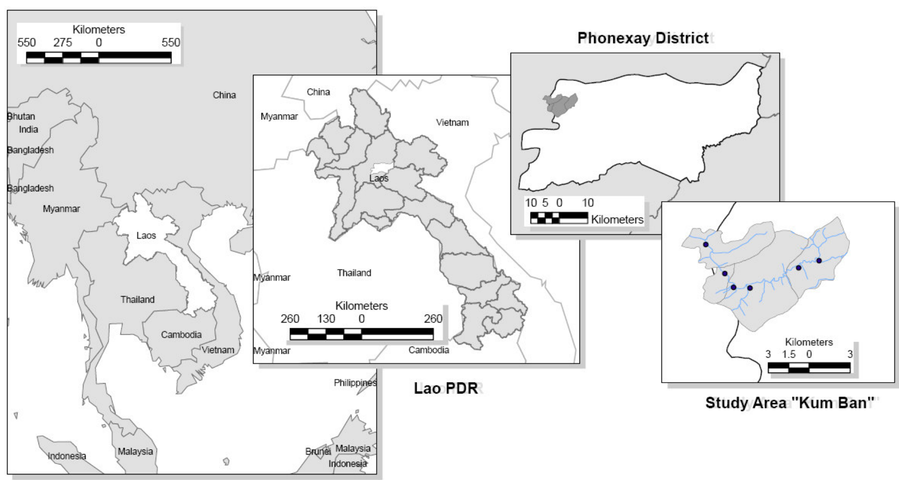


Figure 3. 1. Study area.

3.1. Laos People's Democratic Republic Overview

Among the poorest countries in the world, Laos PDR has been ranked in position 133 for the UNDP Human Development Index (HDI) UNDP (2006). Figure 1.2 shows the HDI for Lao PDR in relation to the GDP per capita and Figure 1.3 shows the HDI in comparison to other regions of the World.

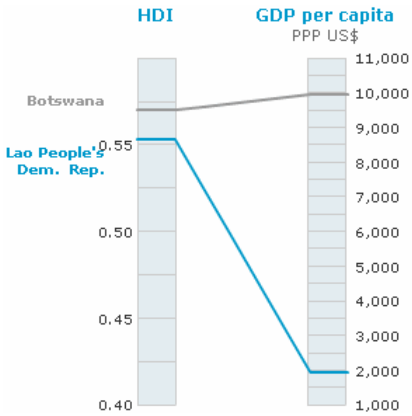


Figure 3. 2. Human Development Index and GDP per capita for Lao PDR. Source: HDR (2006).

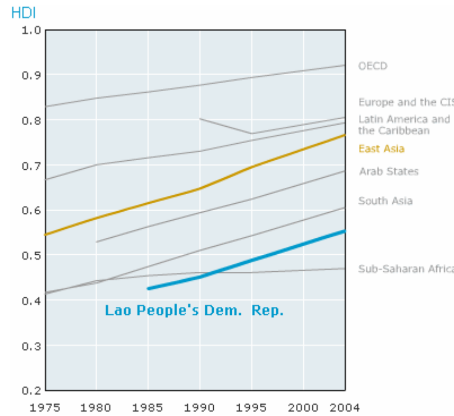


Figure 3. 3. Human Development Index for Lao PDR in comparison to other regions of the World. Source: HDR (2006).

3.1.1. History

In the 14th century, Laos was known as the Kingdom of Lan Xang Hom Khao, and its capital was located in Luang Prabang. Around the 17th century the Kingdom was disintegrated and divided into three states: Luan Prabang, Vientiane and Champassak (UNCDF, 2002). About the 18th century Siam invaded and took control over the principalities. At the end of the 19th century France obtained the control of the three Lao kingdoms that were ceded by the king of Siam and incorporated into the French Indochina in 1893. France united the provinces under the royal house of Luang Prabang.

During the Second World War Japan occupied Laos until 1945; after Japan's surrender Laos Itsara nationalists took the power, but France regained the control and only until 1950 Laos acquired partial autonomy as an "associated state" part of the French Union (Wikipedia, 2006). In 1954 Laos became fully independent as a constitutional monarchy, with French support to the Royal Laos Army against the communist group Pathet Lao, which was supported by the Viet Minh or "League for the Independence of Vietnam". In 1955 elections were held in Laos and a Government of National Union was created, with inclusion of two members of the Pathet Lao; in 1958 this government collapsed and was replaced by U.S control.

The political situation with Vietnam pushed Laos into the Second Indochina War (or Vietnam War), with U.S bombing several areas in the north of Laos with the purpose of eliminating North Vietnamese bases. In 1968 the North Vietnamese Army attacked the Royal Lao Army which resulted in its demobilization and the conflict being left to irregular forces from U.S and Thailand. In 1975, when the U.S involvement in Vietnam was not so strong, the Pathet Lao insurgency, with the support of the Soviet Union and the North Vietnamese Army, overthrown the King Savang Vatthana, whom abdicated that year on December 2. The country was renamed Lao People's Democratic Republic (PDR). From 1975 the country has been ruled by only one party, the Lao People's Revolutionary Party (LPRP).

During the 70s Vietnam exerted a high influence on Laos PDR, but this control was slowly replaced by a reduction of economic restrictions in the 80s as a result of the poor results of the strict national policies. Year 1986 marked the change in economic policies with the New Economic Mechanism (NEM), which allowed free market and economic reforms. Laos had been embargoed by the U.S since 1975, but it was lifted in 1995. In 1997 Lao PDR was admitted into the Association of Southeast Asian Nations (ASEAN). Normal trade relations between U.S and Lao PDR were established in November 2004.

3.1.2. Administration

Lao PDR is composed by 18 Provinces, 141 Districts, 1 special zone in Bokeo province and 10,552 villages (United Nations Development Programme UNDP 2006). The power rests in the only party: the communist Lao People's Revolutionary Party (LPRP) and the Government is run by the Council of Ministers.

3.1.3. Geography

Lao PDR is a landlocked country with a total area of 236,800 km^2 with Thailand, Myanmar (Burma), China, Vietnam and Cambodia as neighbouring countries. Around 70% of the country is mountainous with heights between 1,500 and 3,000 meters. Narrow valleys cross the country thanks to the floodplains of the Mekong and other secondary rivers. Approximately 45% of the country is covered by forests making Lao PDR one of the "most heavily forested countries in SE Asia" UNCDF (2002).

3.1.4. Climate

Climate in Lao PDR is monsoonal with three distinct seasons with some variations between north and south. Between May and October the climate is wet and between November and April is dry. The cool dry season occurs from November to January. In the Mekong valley, temperature can drop to around 15 degrees Celsius and the mountain temperature drop to zero degree Celsius or lower at night. The hot dry season occurs through May; towards the end of this period, there is high humidity and thunderstorms and temperature can reach 35°C. The wet season generally lasts from June until October. It is typified by a consistent pattern of low clouds and rain. Flooding occurs along the Mekong River and some tributaries (Southtravels, 2006).

The average rainfall in the capital Vientiane is 1,700 mm, although in the north of Laos and the highlands it is wetter, with more than 3,000 mm each year. The Table 1.1 displays average monthly climate indicators for Luang Prabang city, (capital of the Province where the study area is located) based on 8 years of historical weather readings.

Table 1. 1. Monthly Climate (°C) and Rain (mm) in Luang Prabang, Lao PDR.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avg. Temperature	21	24	25	25	31	29	28	28	26	26	24	21
Avg. Max Temperature	29	32	32	27	36	32	31	30	29	31	29	26
Avg. Min Temperature	13	15	17	20	23	23	23	23	22	21	18	14
Avg. Rain Days	0	0	0	1	0	0	1	1	2	1	0	0

Source: www.geographyiq.com

3.1.5. Population

According to the National Statistics Centre of Lao (2005), the country has an estimated of 5.65 million inhabitants. The population consists of 49 ethnic groups scattered in 10,552 villages. An average village has 80 households and around 500 inhabitants. Approximately 62% of the population is under the age of 24 years old and life expectancy is 59 years for males and 63 years for females (UN, 2006). An estimated of 82.9% of the population live in rural areas while the infrastructure, social services and job opportunities are in urban areas, which have favoured the increase of young people moving to the cities (UNDP, 2006). Only 53% of the population has access to potable water (UN, 2000).

3.1.6. Education

Around 73% of Lao PDR population are literate, according to the National Statistic Centre of Lao (2005 census) (Figure 3.4). Literacy levels are higher in urban areas (89%) particularly in Vientiane (92%), while in rural areas is low (42%). From the total government expenditure around 11% goes for education (Figure 3.5).

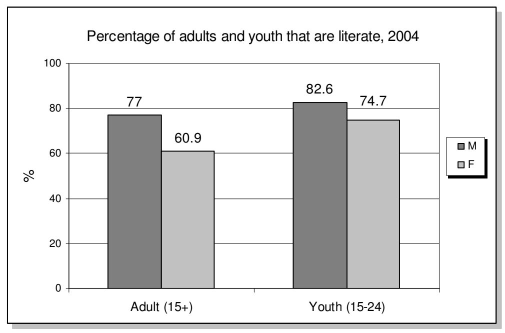


Figure 3. 4. Literacy in Lao PDR. (Source UNESCO, 2004).

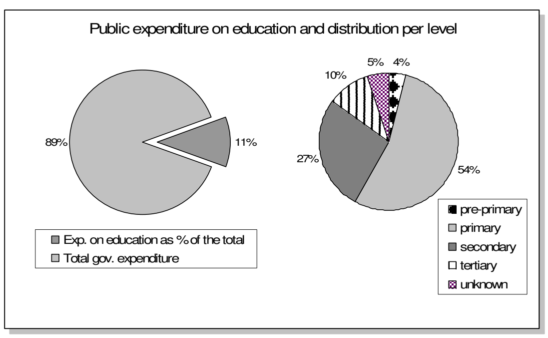


Figure 3. 5. Government expenditure on education and its distribution (Source: UNESCO, 2004).

3.1.7. Poverty and Food Security

Lao population depend on rice for subsistence and households farming systems are organized around rice production. Less than ten percent of the 2 million tonnes of rice produced per year go to the market and under normal conditions it is estimated that a third of the population suffers of rice deficit between 2 to 6 months per year; the situation is worse in upland districts where the deficit in average can be of 4 months (UNDP, 2006).

According to the UNDP (2006):

> *"The agriculture sector suffers from low production and intensity, low productivity and limited diversification. Resources are often not utilized in an optimal or sustainable manner. The subsistence nature of production derives in part from a lack of rural infrastructure, particularly roads, which isolate many villages. Lack of access to markets where surplus production can be sold eliminates the incentive for commercial farming and hinders the development of a market orientated rural economy. Weak market mechanisms, limited transport networks and lack of storage facilities also contribute to a significant loss of the surplus that is generated. Limited technical human resource capacities and institutional structures further constrain agricultural development".*

Geographic conditions also affect the agricultural development of Lao PDR: the mountainous topography and the type of soils limit the available land for cultivations and hamper the infrastructure development (UN, 2006).

3.1.8. Phonexay District and *Kum Ban*

Phonexay District is located in the north of Lao PDR, and belongs to Luang Prabang Province. According to NAFRI (2004) Phonexay is the poorest district in the province and one of the ten priority districts for development programs. The capital of Luang Prabang Province is the city of the same name, which used to be the capital of the country.

The group of villages or *Kum Ban* selected for this study is located in the center of Phonexay District (see Figure 3.1). These villages have been selected because rubber is a complete new crop in the area (the first rubber seedlings were planted two years ago), the villages are some of the poorest in the district, which make them an important target for development programs, and because of the data available (a result of the interest in their development). The total area of the *Kum Ban* is 5,670.5 hectares.

Three main ethnic groups can be found in the area: Lao Soung (LS, or Hmong Khao), Lao Theuang or (LK, or Khmu), and Lao Loum (LL). All the ethnic groups can be found in each village, but the main groups by village are:

- Thapo: Lao Soung and Lao Theuang
- Nambo: Lao Theuang and Lao Soung
- Houaymaha-Poungpao: Lao Soung and Lao Theuang
- Houayman: Lao Theuang and Lao Soung

According to NAFRI (2004), the wealth categories for the households have been given by the head of the village according to the food available:

- Category 1: Surplus food
- Category 2: Sufficient food
- Category 3: Insufficient food
- Category 4: Poor
- Category 5: Very poor

Table 3.1 presents the wealth category and ethnic composition of the target villages.

Climate in the Study Area

According to NAFRI 20002, the climatic data was derived from the Oudomxai Meteorological station. The climate is wet/dry monsoon tropical, classified as an "Aw" Koppen type. The average rainfall is 277.68mm and the mean temperature is 22.7 °C. There are two main seasons: the Wet that begins from May and lasts until late September, with a total rainfall of 1,038.64 mm; and the Dry season from October to April, with July and August as rainy months, with a rainfall of 514.08mm.

The mean temperature in the area varies the whole year, with a maximum mean temperature of 26.08 °C in May and June and a minimum of 17.20 °C in December.

NAFRI (2002) states that the rainfall exceeds the evapotranspiration (ETP) throughout the wet season, while in the dry season the rainfall is below the ETP. The planting of crops during the dry season requires additional water supply to complete the crops life cycle.

Table 3. 1. Ethnic groups distribution and wealth categories for the target villages.

THAPOTAI	Number	% of total
Total HH	122	100%
Ethnic composition of village		
LS	77	63%
LT	43	35%
LL	2	2%
Wealth categories		
1	24	20%
2	52	43%
3	28	23%
4	10	8%
5	8	6%

THAPONEUA	Number	% of total
Total HH	122	100%
Ethnic composition of village		
LS	77	63%
LT	43	35%
LL	2	2%
Wealth categories		
1	24	20%
2	52	43%
3	28	23%
4	10	8%
5	8	6%

NAMBO	Number	% of total
Total HH	62	100%
Ethnic composition of village		
LS	23	37%
LT	32	52%
LL	7	11%
Wealth categories		
1	20	32%
2	29	47%
3	12	19%
4	1	2%
5	0	0%

HOUAYMAN	Number	% of total
Total HH	48	100%
Ethnic composition of village		
LS	9	19%
LT	35	73%
LL	4	8%
Wealth categories		
1	9	19%
2	13	27%
3	6	12%
4	8	17%
5	12	25%

HOUAYMAHA	Number	% of total
Total HH	122	100%
Ethnic composition of village		
LS	77	63%
LT	43	35%
LL	2	2%
Wealth categories		
1	24	20%
2	52	43%
3	28	23%
4	10	8%
5	8	6%

Physiography and Geology

NAFRI (2002) identified the principal physiographic units as alluvial flood plains, valleys, undulating low terraces, undulating high terraces and rolling foot slope and hills. The geology of the area belongs to the recent Quaternary, Lower Jurassic and Permian to Upper Carboniferous formations such as River alluvium, Older alluvium and Lateritic surfaces. Figure 3.2 presents a 90mx90m DEM for the study area; the villages are located along the valley of the Nampa River.

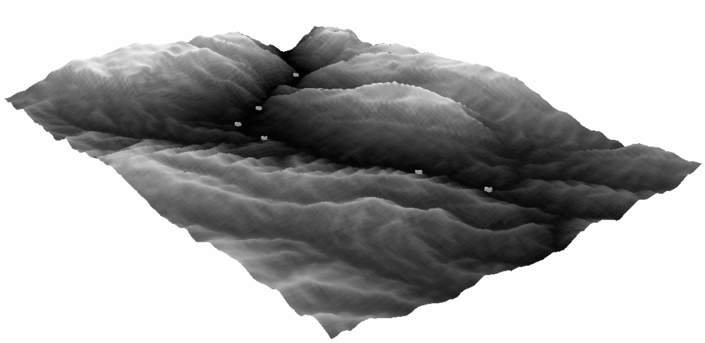


Figure 3. 6. DEM for the study area and villages location. (SRTM *http://seamless.usgs.gov/*)

Vegetation and land use pattern.

The natural vegetation and present land use in the study area can be described as mixed deciduous forest, related to soil types and water regime. The tropical mixed deciduous forest comprises moist and dry forest, that occur mainly on undulating high terraces and rolling foot slope hills. In the area the top canopy forest are composed by *pterocarpus dalbergioides*, *terminally pialata, largerstroemia*, *shorea robusta* among other species; these species can be found on undulating low to high terraces (NAFRI, 2002). The land use patterns in the study area can be broadly grouped as rain fed paddy rice, agricultural plantations, ray/shifting cultivations, forest plantations, temporarily unstocked forest and mixed deciduous forest (NAFRI, 2002). Upland rain fed rice and rubber fall into the agricultural plantations class.

Infrastructure

Two main roads cross the study area. These roads are unpaved and are maintained by the community. Tracking roads can be found crossing the different villages. The tracking roads go trough steep slopes and areas with forests and cultivations. Figure 3.3 shows the main roads and the tracking roads in the *Kum Ban*.

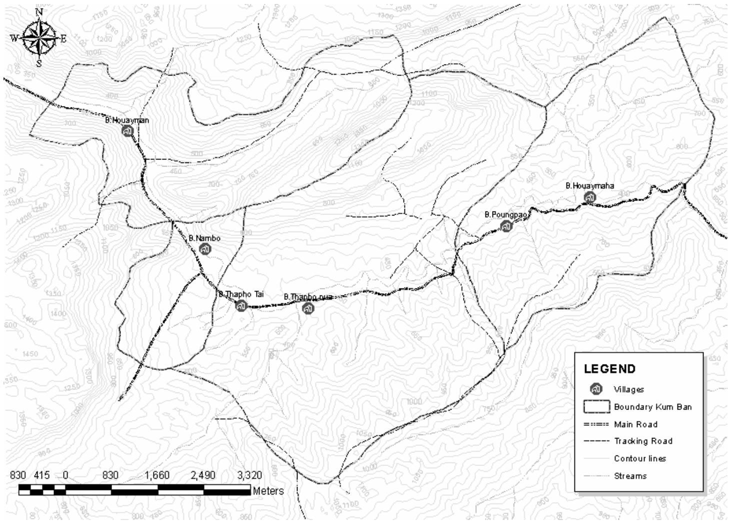


Figure 3. 7. Main roads and track roads in the study area.

Soils

The system of soil classification used by the Soil Survey and Land Classification Centre (SSLCC) for Nam Bo area was derived from the FAO/UNESCO legend soil map of the world, 1989 revised legend (NAFRI, 2002). The SSLCC produced the soil map for the Phonxay District using physiographic maps and aerial photographs.

In the field soil units were delineated according to morphological characteristics. Soil samples were taken from pits with different genetic horizons and auger sampling was carried out with a density of one per every 60 ha; the same density was used for the pits samples. The samples were analysed in the laboratory of soils of NAFRI. With the survey and laboratory results the soil subgroups were determined and the soil map digitised.

The system of soil classification has two categories, i.e. soil groups and soil subgroups (units). The classification was based on soil properties and diagnosis observed in the field or implied from observation or on laboratory measurements. Three groups of soil can be recognized in the area: Leptosols, Cambisols and Acrisols. Sub-groups or soil units were distinguished within the three soil groups, based on the properties that influence soil genesis and are important to plant growth. The main subgroups are Eutropic Leptosoils, Eutric Cambisols and Haplic Acrisols. A detail record of the type of soils can be found in the reports prepared by NAFRI (2002) for each village.

The areas delineated on the soils map were labelled using a code that refers to dominant soil group in capital letters and subgroups (soil units). Then the soil codes were combined with soil depth class, soil texture, slope class and assessed top soil fertility. The complete combination code is given in the following example:

CMe-D-La (M) Where

	CM	-	CAMBISOLS.
	CMe	-	Eutric CAMBISOLS
	D	-	Deep (>100 cm depth)
	L	-	Loam texture.
	b	-	Flat or almost flat physiography with 0 to 2% of slope
	(M)	-	Medium topsoil Fertility

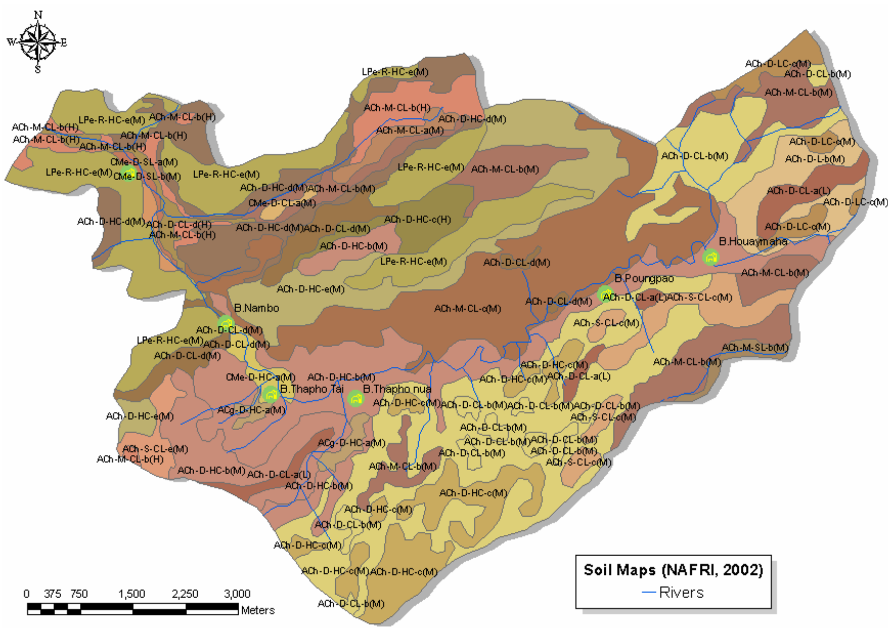


Figure 3. 8. Soils in the study area (NAFRI, 2002).

3.2. Description of Agriculture Conditions in Phonexay

In Lao PDR and in particular in Phonexay District most of the farmers own the land but they can not sell it. Each farmer has a certain number of plots that varies depending on the District regulations and the farmers' income. In Phonexay the farmers are allowed to have up to four plots, each plot having 1 hectare. Plots are distributed along the whole extension of the administrative boundaries of the village:

farmers live in the villages that are located along existing roads while the plots can be as far as two hours walking. These plots are used rotationally to cultivate principally rice and cash crops such as eagle tree, sesame, teak, jobstear and in some cases corn and fruit trees.

Due to the topography the land available for cultivation is located on steep slopes. The valleys are narrow, so few paddy fields are available in comparison to the total land area that can be used for upland rice fields.

Photo 3. 1. Valley of the Nampa river

In the *Kum Ban* no irrigation systems are employed and no terraces are found on the mountains. The labour is manual, no machinery or animal force is employed. Farmers do not use fertilizers and pesticides are used just in extreme cases. Farmers rely on fallow period as a way for the soil to recover its nutrients. The older the fallow the better the yield and the number of times the plot can be used.

The process for cultivation starts with the slashing, cutting and burning of trees (for an old fallow); then seeds are planted. In the case of upland rice, three times per season weeding is required: After the first month and then every two months. Members of different families of the village help the owner of one plot or group of plots with the whole cultivation process.

Once the yield has been produce, the farmers harvest and carry the products to the village, where the middlemen come on a daily basis to buy the products. In the study area, villages have been relocated to place them close to the existing roads and existing facilities such as health services.

The distance and access to the crops reduce the feasibility of certain cultivations like pineapple or corn: farmers have to walk around 1 to 2 hours to their fields which make difficult transportation and surveillance of their crops. Pineapple, corn and similar crops can be stolen easily. Furthermore, they have to carry their products on their backs which can be difficult for certain products such as pinneaple.

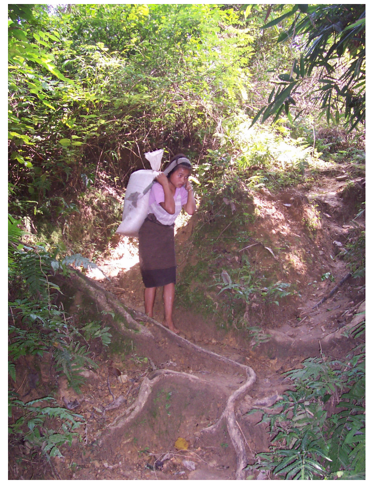


Photo 3. 2. Young woman carrying rice along steep slope.

Farmers perceive the market as unstable for cash crops, but for rice and staple food there is always a market. Given the experience in other villages and the manifested interest of China, farmers in the study area have a feeling of confidence about the potential demand of rubber.

Photo 3. 3. Women arriving to Thapo village.

4. RESEARCH APPROACH

4.1. Introduction

This chapter describes the data used and the methodology followed during the research process. The data can be divided into two: secondary data extracted form diverse agencies under the coordination of NAFRI and the collected field data. All the data collection was carried out through NAFRI and related agencies existing in Lao PDR under the support of the Swedish International Development Cooperation Agency SIDA.

The research methodology has been divided into three sections, each of them corresponding to one output of the study. The first part deals with the Farmers' Soils and Land Suitability Maps, the second part reports the land suitability evaluation on the basis of expert system concept (that is, the inclusion of experts knowledge and farmers' perception) where the FAO framework for Land Evaluation (1978) is employed, and the third part describes the methodology to obtain suitability maps using Fuzzy Modelling applied for Land Evaluation.

The Figure 4.1 is a flow chart that summarizes the research methodology. Once the problem has been defined, literature about land evaluation and fuzzy modelling has been reviewed (Chapter 2), then the data requirements for the land evaluation have been determined. The available data was prepared and extra data, both secondary and field was obtained through NAFRI. The field data involved the definition of the land utilization types, information reagarding farmers' perception about suitability and maps with the suitability for rubber and upland rice prepared by the farmers. The retrieved secondary data (i.e. shape files and soils laboratory results) was validated and verified to perform the land evaluation under the Boolean theory and the fuzzy theory. Finally, the three land evaluation maps (Boolean, fuzzy and farmers') were compared to asses their relative performance. The final results were analysed and discussed (Chapter 5).

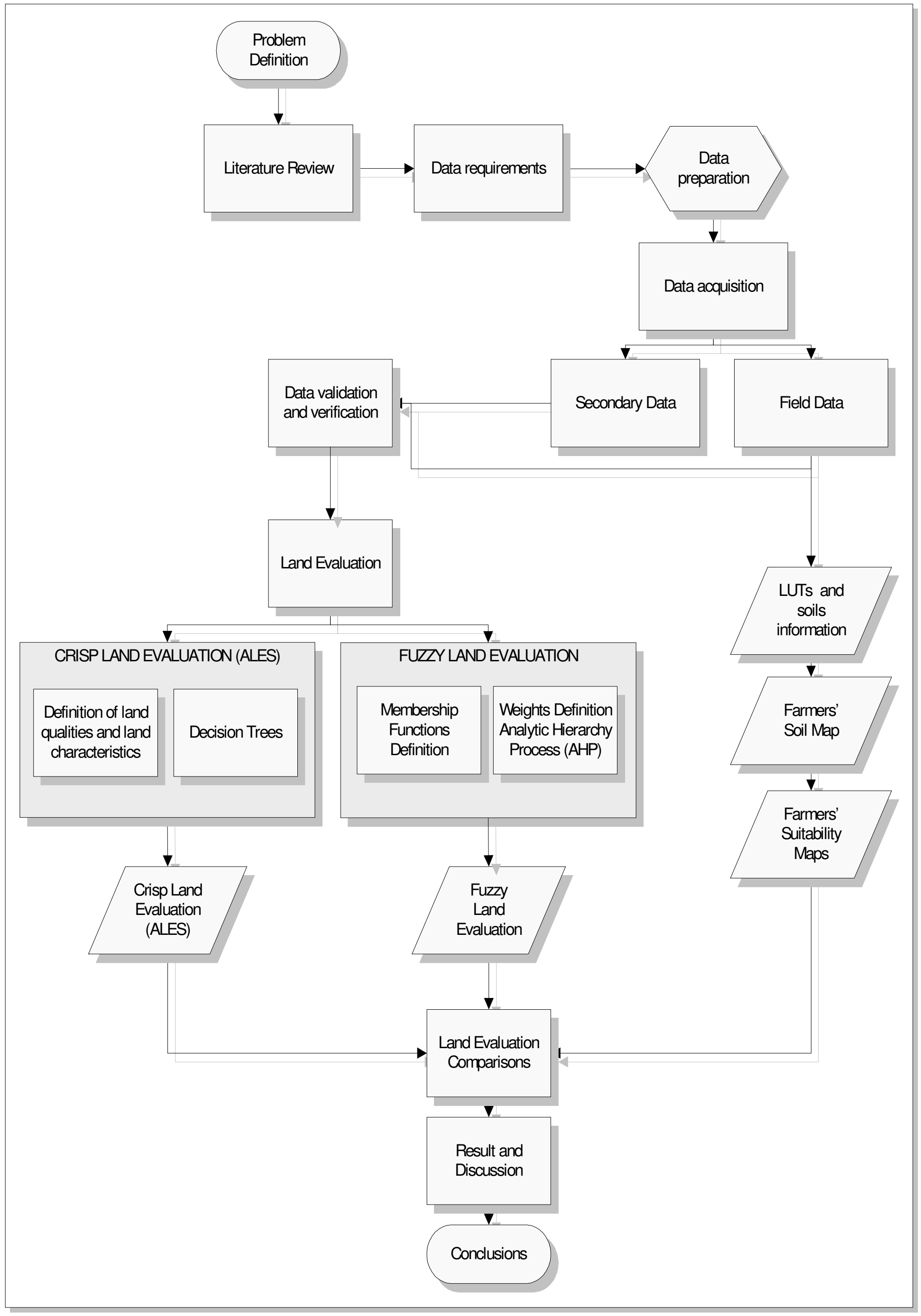


Figure 4. 1. Research Methodology

4.2. Data Collection

4.2.1. Secondary Data

The secondary data collected from NAFRI consisted in ArcGIS® shapefiles and digital and printed out reports. All the spatial data was re-projected into the UTM WGS 1984 system for the Zone 48 N.

An ASTER image from November 2000 was used for georeferencing and identification purposes, and a Digital Elevation Model DEM was obtained through the USGS SRTM website *http://seamless.usgs.gov/*, with a resolution of 90x90m. Table 4.1 shows the main datasets employed in the study.

Table 4. 1. Datasets employed in the study

Shapefile	Type	Description
Soil4villages	Polygon	Soils for the four villages
Landusenew	Polygon	Land use
River4village	Line	Rivers in inside the 4 villages
villageP	Point	Villages in the district
Laoprovince	Polygon	Luang Prabang Province
BND4village	Polygon	Administrative boundary of the 4 villages
Roads4village	Line	Roads in the village
DEM	raster	SRTM
ASTER	raster	Multispectral image

Due to the small size of the study area, the climatic conditions are quite homogeneous and were not included in the models.

4.2.2. Field Data

The field data collected consisted in georeferenced soil samples, interviews and sketches of the current land use. The formats for interviews employed by NAFRI representatives appear in Appendices 1 and 2 in Lao and English respectively. The soil samples were georeferenced using a Mobile GIS system (de Bie 2002). This system consists of an ESRI ArcPad® (v.6.0.3) software installed in a Hewlett Packard®-iPAQ® Pocket PC connected to a Garmin® Global Positioning System (GPS). An ASTER orthorectified image was loaded in the system to facilitate the identification and referencing processes.

4.2.3. Data Migration

The soils datasets provided by NAFRI consisted in independent tables, one per village, including the soil principal characteristics. Laboratory results and additional data were compiled in different tables. The soils map for the *Kum Ba*n was stored in a digital shape file format, with the soil unit name as identifier for each polygon. To add the soil characteristics in the corresponding soil unit from the shape it was necessary to generate a Personal Geodatabase.

The soil shape file was divided by villages to facilitate the data comparison. The original tables with the soil characteristics by village in Excel format were linked to the shapefile and the data was transferred by queries in Microsoft Access® using the soil unit and the village name as identifiers. This migration process was carried out until all the units of the soil map had the attributes from the laboratory results.

The soil depth in the tables from NAFRI is given profile-based and in words, such as deep (D), moderate (M), surface (S), thin (T) or rock outcrop (R), without numerical value. In these cases the lower limit of the class was considered: e.g. according to NAFRI a deep soil has a depth greater than 100 cm. If for a particular unit no value was given, but the depth was indicated as D, 100 cm –the lower limit- was assigned.

4.3. Farmers' Soils and Land Suitability Maps

With the purpose of creating maps that represent the farmers' perception of the soils and their potential use "group discussions" with household representatives of the four administrative villages were carried out by NAFRI representatives. In these meetings a topographic map scale 1:25000 and a satellite image (ASTER, 1:25000, from November 2000) were used as reference for the farmers.

After identifying the main rivers and topographic features such as mountains and valleys, the farmers delineated on a tracing paper the soils they can recognize in the area. The topography and the position of the rivers were the main patterns employed to identify the soils location and their characterization was given by colour and in some cases by texture and rockiness. Once the soils map for the whole village was created the farmers were inquired about the potential use of the soil units they described. In this way suitability maps according to the farmers' perception were obtained.

During the discussion meetings, members of NAFRI carried out interviews regarding land management, tenure, cultivation techniques, income, labour intensity, farm size, accessibility among others. In each village between 6 and 8 farmers were interviewed independently using a questionnaire; additionally, open questions were posed to all the participants of the meetings with the objective of corroborate complement the answers given by the farmers. The format for the interviews was originally prepared in English and translated into Lao by personnel of NAFRI.

To understand the way the farmers describe the colour, random points were selected and verified. In these points the colour was described based on the Munsell soil colour charts (1975). Other parameters measured or verified were soil pH (using a field pH kit), soil texture, slope, elevation, position, land cover and land use. Figure 4.4 shows the location of the points surveyed. Figure 4.2 show the variation between pH in laboratory and field and 4.3 the variation between depth in the field and in the soil maps.

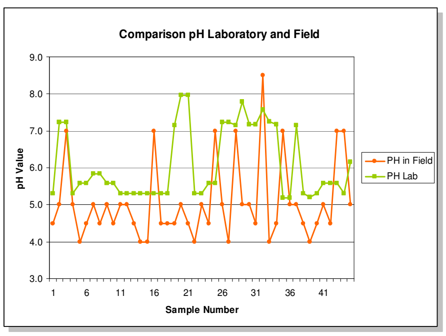


Figure 4. 2. Comparison of pH in field and in laboratory.

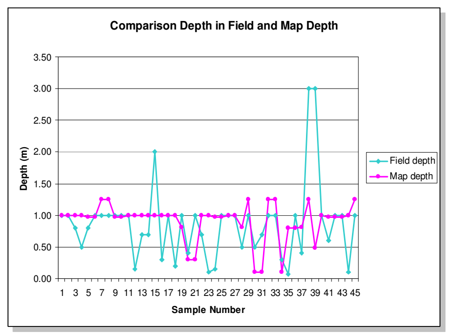


Figure 4. 3. Comparison of depth in the field and in maps.

Figure 4.5 presents the farmers' soils and the experts' soil classification. It can be noticed an overall tendency. Farmers delineated the soils based on topographic features in a similar way as experts do, but with a different level of generalization.

Using the ASTER image and topographic maps for the study area, a current land use map was drawn. The topographic features were used to sketch the existing cultivations on the field (Figure 4.6). After creating the soils map, the farmers defined the suitability of the different soil units for different crops, including upland rice and rubber. The farmers' suitability map can be seen in Appendix 18.

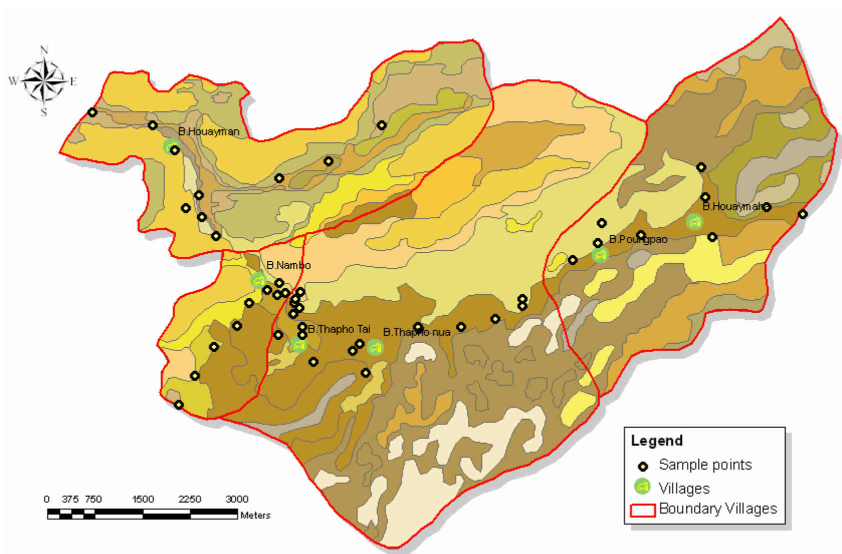


Figure 4. 4. Sample points in the study area.

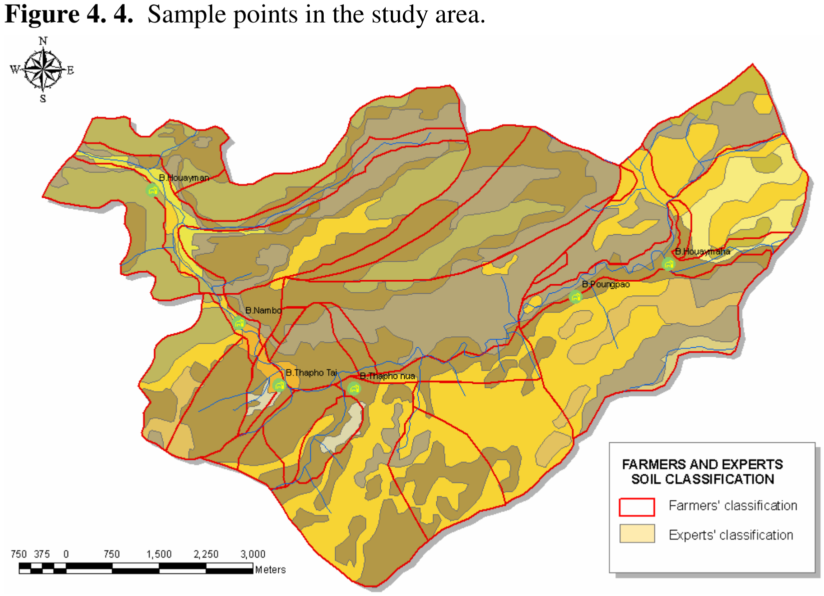


Figure 4. 5. Farmers' and Experts soil classification.

Figure 4.6 presents the sketch of the current cultivation in the study area. In red the areas identified with current rubber plantations and in orange the areas with upland rice. The soil classification based on colours assigned by the farmers has been compared to the experts' soil classification and the sample points in the field. The results appear in Appendices 3, 4 and 5. It can be noticed that farmers assigned four basic colours to the soils: yellow, red, beige and black, with their possible combinations. Farmers also distinguished basic textures such as sandy loam and stoniness.

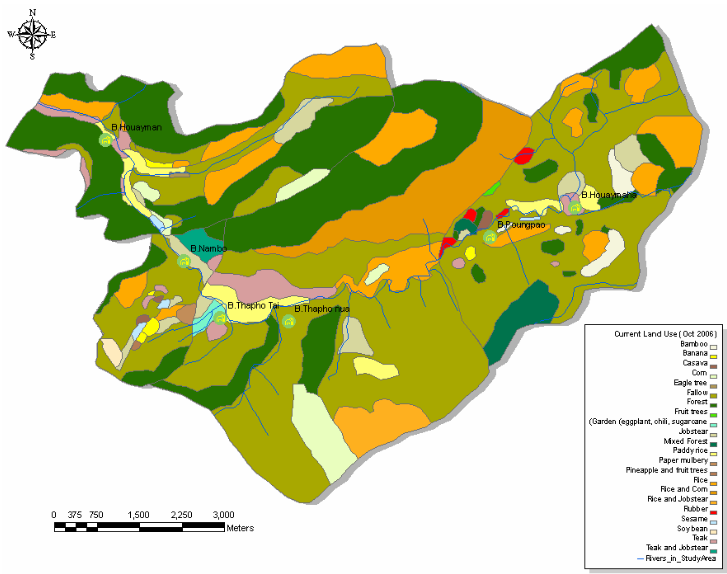


Figure 4. 6. Sketch with current cultivations in the study area (prepared by Kayasone, 2006).

4.4. FAO Framework for Land Evaluation

FAO framework for Land Evaluation (1978) was used to assess the suitability of rubber and upland rice in the *Kum Ban* composed by the villages Thapo, Nambo, Houaymaha-Poungpao and Houayman. From the interviews, experts and literature (1991), the land use requirements or land qualities necessary for the target cultivations were obtained and expressed as land characteristics. A database with the land qualities, land characteristics, map units and decisions for suitability was constructed in the Automated Land Evaluation System ALES v. 4.65 developed by Rossiter and Wambeke (1997). The map units employed in the land evaluation analysis correspond to the soil map units present in the area. The model was run for three different fallow periods. The suitability assessment in ALES is based on matrices and decision trees that allow the comparison between land characteristics. Appendix 6 presents the input parameters for the map units of the study area, and Appendix 7 presents the decision trees for both land utilization types.

4.4.1. Land Utilization Types

The land utilization types (LUTs) considered in the land evaluation were upland rain fed rice and rubber. The selection of rubber was given by the farmers' interest on rubber due to market demand from China; upland rice is the staple food from the villages. Table 4.2 shows a summary of the LUTs considered for this research.

Upland rainfed rice

This crop is cultivated by small holders on plots with 1 ha size. All the process is traditional. Farmers slash and burn bushes and existing trees. The soil is ploughed to sow the seeds. Land is weeding three times during the season, after the first month, and then every two months. The yield is carried by the farmers (in sacks on their backs) from the plots to the villages, where the middle man comes to buy it. No irrigation or fertilizer is used.

Rubber

Rubber is planted with crops like pineapple, corn and other cash crops. To prepare the land the existing trees and bushes from the fallow period are slashed and burnt. The seedlings are planted in holes made in the soil. The oldest trees in the study area are between two and three years old, and at least 7 are required for the first yield.

Table 4. 2. Quantifiable Factors for Land Utilization Types in The Study Area, Phonexay District, Lao PDR

No.	LUT	Produce	Capital intensity U$/ha	Labour intensity man-months per ha	Farm power	Level of technical knowledge	Farm size ha/household	Land tenure	Incomes: value added (approx.) U$/ha	Observations
1	Rubber	latex	Low*	1	manual	traditional	2-4	own	Low*	No rubber production in the area yet. Data source: NAFRI and interviews
2	Upland rainfed rice	upland rice	Low*	1	manual	traditional	2-4	own	Low*	Source: Interviews

Capital intensity: Low: 500-700-Medium: 700-1000-High: >1000 Income: Low: 600-900-Medium: 900-2000-High:>2000

4.4.2. Land Qualities and Land Characteristics

Six land qualities were considered for upland rice and rubber but with different limiting factors given by their corresponding land characteristics, as shown next.

Table 4. 3. Land qualities and land characteristics for upland rice.

LAND QUALITY	LAND CHARACTERISTIC	UNITS	RATING			
			s1	s2	s3	n
Soil fertility	Fertility	Class	High	Medium	Low	None
	Fallow	Class	Old	Medium	Young	No fallow
Moisture availability	Soil texture	Class	CL, SC, C	L	SL	HC
	Soil depth	cm	30-200	20-30	10-20	0-10
Rooting conditions	Soil depth	cm	50-300	30-50	-	0-30
Erosion hazard	Slope	%	0-20	20-50	50-100	100-200
	Observed erosion		None	Low	Moderated	High
Workability	Slope	%	0-20	10-20	20-50	40-200
	Soil texture	Class	SC, SL	CL, L	C, HC	R
	Fallow period	Yr	4-7	2-4	1-2	0-1
	Soil depth	Class	75-300	50-75	30-50	0-30
Accessibility	Slope	%	0-20	10-50	50-100	100-200
	Proximity to villages	M	0-500	500-1000	1000-2000	2000-5000

Table 4. 4. Land qualities and land characteristics for rubber.

LAND QUALITY	LAND CHARACTERISTIC	UNITS	RATING			
			s1	s2	s3	n
Soil fertility	Fertility	Class	H	M	L	N
	Fallow	Class	OF	MF	YF	NF
Moisture availability	Soil texture	Class	CL, SC, C	L	SL	HC
	Soil depth	cm	100-500	50-100	30-50	0-30
Rooting conditions	Soil depth	cm	100-500	70-100	50-70	0-50
Erosion hazard	Slope	%	0-20	20-50	50-100	100-200
	Observed erosion	Class	N	L	M	H
Workability	Slope	%	0-20	10-20	20-50	50-200
	Soil texture	Class	SL, CL, L, HC	-	-	-
	Fallow	Yr	NF	YF	MF, OF	-
	Soil depth	cm	-	-	-	0-30
Accessibility	Slope	%	0-20	10-20	20-40	40-200
	Proximity to villages	m	0-500	500-1000	1000-2000	2000-5000

Tables 4.3 and 4.4 were prepared to summarize the available information which is used to establish the decision trees in the model in ALES.

A brief description of the land qualities and land characteristics is given next.

Soil fertility: This land quality has been assessed based on two land characteristics: fertility and length of fallow period. According to the farmers, the fallow allows the soil to produce better yields. It means that fallow is important for the soil to recover its nutrients. The fertility of the soil has been established using the same parameters employed in the reports "On Soils & Land Suitability" prepared by NAFRI (2002) for the study area; these parameters are: percentage of organic matter, base saturation percentage (BS%), cation exchange capacity (CEC), available phosphorus, and available potassium. For fallow, four different periods have been assumed for the whole area: No fallow (0 years), young (1-2 years), medium (2-4 years) and old fallow (more than 4 years). The main reason to assign the same fallow for the whole study area was the difficult to determine the number of fallow years in the different plots and to evaluate how fallow affects the final suitability. The criteria employed by NAFRI to evaluate soil fertility are presented in Table 4.5. Where no data on cation exchange capacity and base saturation was available, NAFRI used pH combined to phosphorus and potassium to evaluate fertility.

Table 4. 5. Criteria for Fertility Evaluation

CRITERIA	% Organic matter	% Base Saturation	Total of cation exchange capacity	Available Phosphorus	Available Potassium
	(%OM)	(%BS)	(CEC-Tme/100g of soil)	(P_{PPM}) (BRAY-II method)	(K2Omg/100 g of soil)
Low	<2.0	<50	<10	<10	<4.0
(Rate)	(1)	(1)	(1)	(1)	(1)
Medium (M)	2.0-4.0	50-75	10-20	10-25	4.0-12.0
(Rate)	(2)	(2)	(2)	(2)	(2)
High (H)	>4.0	>75	>20	>25	>12.0
(Rate)	(3)	(3)	(3)	(3)	(3)

Indices <=7; Low fertility (L)
Indices 8-12; Medium fertility (M)
Indices >=13; High fertility (H)

Moisture availability: Two land characteristics were employed to assess this land quality: soil texture and soil depth. The texture of the soil controls its water retention, and combined with the depth of the soil it controls the amount of water available for the crop or plantation.

Root conditions: The optimal conditions for rubber to grow are given when at least 1 meter of soil depth is available for its roots to penetrate the soil (rooting zone). In the case of rice a minimum of 50 cm is required.

Erosion hazard: This land quality was assessed using slope and the observed erosion. With high slopes the potential of erosion is increased. The observed erosion was evaluated in the field based on the places where exposed soil or land degradation was detected. The main constraint of this method to asses the erosion is that it generalizes the erosion conditions for a soil unit: if two points with high levels of erosion were observed there is a chance of assigning to the whole soil unit a high risk of erosion, while in reality these points could have been isolated cases.

Workability: In the case of upland rice, where the farmer ploughs the land in a traditional manner, the texture of the soil has a role on its workability and if the soil is shallow (with hard textures or rock underneath) it can be difficult to plough. For rubber, soil texture is not so important unless the soil is extremely hard: rubber just requires a hole to be dig to put the seedling. Given the cultivation techniques employed in the area the fallow period may cause difficulty regarding workability as well: with a long fallow more vegetation has to be slashed and burnt. For upland rice the farmers have to weed at least three times per season. In the case of rubber, weeding is also necessary. Slope plays a role mainly when it is very steep, that is above 100%. A high slope combined with an old fallow makes the workability quite difficult.

Accessibility: This land quality was assessed using the combination of two land characteristics: slope and proximity to the villages. In the study area, the farmers live in villages located near to the main roads, but their plots can be as far as two hours walking on steep slopes. Accessibility may affect the maintenance of the crops at the initial stages of cultivation and the yield collection. Once the yield has been produced farmers have to walk with the products back to the village using the available tracking roads. To determine how far a village is from the different map units buffers with different distances were created. If most of the area of a map unit falls into a category of distance, this distance value is assigned to the map unit. Figure 4.7 shows the buffers around villages with the corresponding map units.

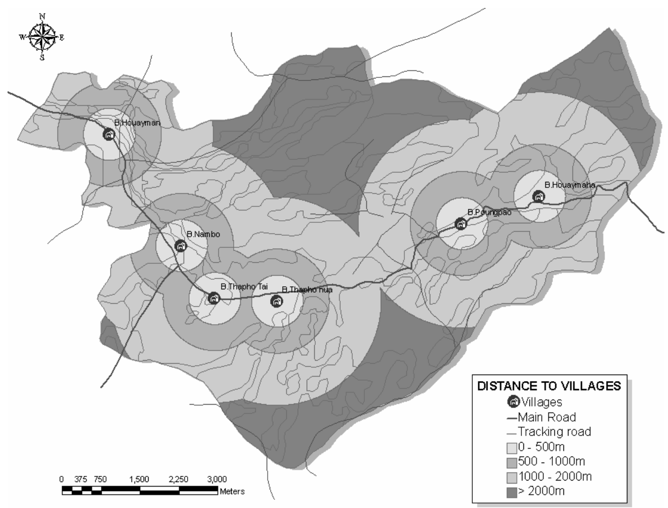
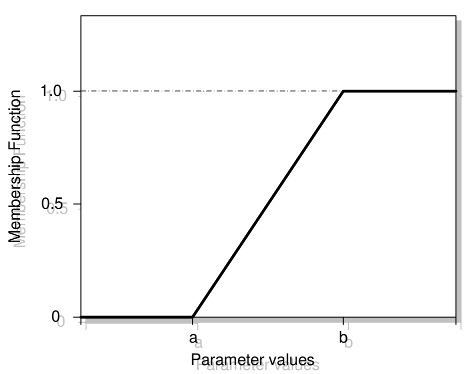


Figure 4. 7. Determination of distances of soil units to the villages using buffers and areas values.

4.5. Fuzzy Modelling for Land Evaluation

In order to make comparisons between Boolean and fuzzy theory for land suitability, the same land qualities and thus the same land characteristics were applied. The input maps were rasterized using 5x5m cells, with the exception of slope, that was derived from a DEM with 90x90m resolutions. In the crisp methodology fertility was the combination of organic matter, total base saturation, cation exchange capacity, available potassium and available phosphorus in the soil. In the fuzzy methodology the same parameters have been considered for fertility, but without taking into account pH, which may have strong fluctuations within the same soil unit.



The calculation of the fuzzy memberships for the different factors influencing fertility was evaluated using a linear function as given in the Figure 4.8 and in Equation 4.1.

Figure 4. 8. Linear or asymmetrical triangular membership function.

$$\mu_A(x) = \begin{cases} 0 & x \le a \\ \dfrac{x-a}{b-a} & a < x < b \qquad a < x < c \quad x \in X \\ 1 & x \ge b \end{cases} \qquad \text{Equation 4. 1}$$

Where x is the input data and, *a* and *c* are the limit values according to Tables 4.4 and 4.5. This function has been used considering a proportional and linear increment of fertility with the increase of each factor and was employed by Schubert (2005) for Sri Lanka with satisfactory results.

For depth an asymmetrical second grade function has been employed:

$$\mu_A(x) = \begin{cases} \dfrac{1}{1 + a \cdot (x-c)^2} & x < c \\ 1 & x \ge c \end{cases} \qquad x \in X \qquad \text{Equation 4. 2}$$

This function was tested successfully by Burrough (1989) for soil depth. In the equation, *a* is a parameter that controls the shape of the function and the position of the cross-over points; the expression $(x-c)^2$ controls the dispersion (Figure 4.8)

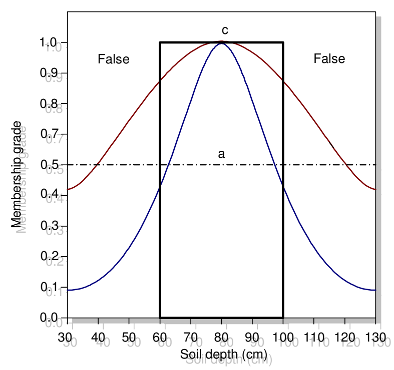
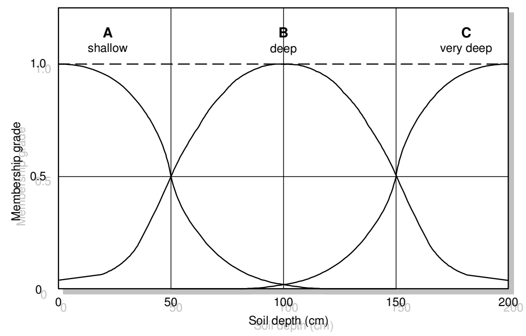


Figure 4. 9. Membership function for asymmetrical second grade function (adapted from Burrough, 1989).



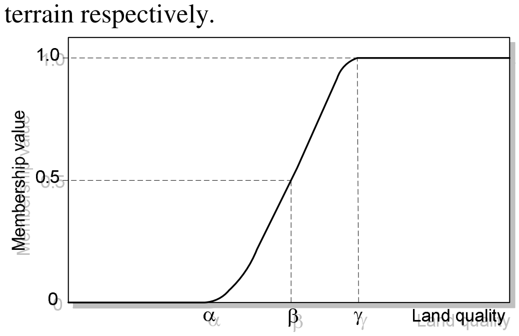
Mc Bratney *et al* (1997) employed a combination of symmetrical Gaussian functions to assess the membership functions for depth. In this way the overlapping nature of soil depth can be assessed.

Figure 4. 10. Gaussian membership function for fuzzy subsets of soil depth.

In this work, the equation 4.2 has been employed to determine the membership function for depth due to its simplicity and the format of the input data (a single value of depth for each top soil unit in the study area).

$$S(x;\alpha,\beta,\gamma)=\begin{cases} 0; & x \in \left]-\infty,\alpha\right[\\ 2\left[(x-\alpha)/(\gamma-\alpha)\right]^2; & x \in \left[\alpha,\beta\right[\\ 1-2\left[(x-\gamma)/(\gamma-\alpha)\right]^2; & x \in \left[\beta,\gamma\right[\\ 1; & x \in \left[\gamma,+\infty\right[\end{cases}$$ Equation 4. 3

For slope, an S membership function was employed, as defined by Tang *et al* (1991). The limits α and γ corresponded to the limit conditions of steep slopes and flat terrain respectively.



According to Burrough (1996) this function gives better results when compared to other membership functions, and for this reason has been used.

Figure 4. 11. S membership function (adapted from Tang *et al*, 1991).

4.5.1. Weighting Parameters

The weighting parameters represent the relative importance of the suitability of each factor in relation to the other factors contributing for the suitability. Weighting parameters for land evaluation can be obtained based on experience, on statistical analysis or through an Analytic Hierarchy Process (APH). The latter, a combination of experience and a mathematical process, was chosen due to its relative simplicity, the characteristics of the data and because it allows assigning different levels of importance to the different parameters involved in land suitability.

Analytic Hierarchy Process (AHP) was developed by Thomas Saaty in the 1970s (Saaty and Vargas 2001). The AHP is a method that facilitates the selection of weighting criteria and admits the decision making when there are a limited number of choices, each choice with attributes that are difficult to formalize. AHP relies on Pair wise Comparison Matrices which are matrices relating different components and assigning values according to their relative importance. These values are given by a scale from 1 to 9, where 1 means that the two elements being compared have the same importance and 9 indicates that from the two elements one is extremely more important than the other. The table with the scale for Pairwise Comparison is shown in Table 4.6.

Table 4. 6. Fundamental Scale for Pairwise Comparison
(Adapted from Saaty and Vargas 2001)

Numerical Value	Verbal Scale	Explanation
1	**Equal importance**	**Two elements contribute equally**
2	Weak	
3	**Moderate importance**	**One element slightly favoured over the other**
4	Moderate plus	
5	**Strong importance of one element over another**	**One element strongly favoured over the other**
6	Strong plus	
7	**Very strong or demonstrated importance**	**An element is favoured very strongly over another, with this dominance being demonstrated in practise**
8	Very, very strong	
9	**Extreme importance of one element over another**	**Evidence highly favours one element over another**
Reciprocals	If one element *i* has one of the values given above when compare to j, the element j has the reciprocal value when compared to *i*.	

For the different parameters composing the land suitability, their relative importance was assigned. The Table 4.7 shows the Pairwise Comparison Matrix for Fertility. As in the Boolean land suitability assessment, fertility has been estimated using the same categorization given in Table 4.5.

Table 4. 7. Pairwise Comparison Matrix for Fertility

ELEMENTS	Cation exchange capacity	% Organic matter	% Base Saturation	Available Phosphorus	Available Potassium	Weight
Cation exchange capacity	1	4	3	7	7	0.463
% Organic matter	1/4	1	1/5	5	5	0.144
% Base Saturation	1/3	5	1	6	6	0.298
Available Phosphorus	1/7	1/5	1/6	1	1	0.047
Available Potassium	1/7	1/5	1/6	1	1	0.047

As an example, organic matter has been considered more important than available potassium and received a value of 5 when compared to it, while potassium when compared to organic matter received its reciprocal, 1/5. The final weight is the result of dividing each record value by the sum of the respective column and then calculating the average for the corresponding row.

The relative importance of the different land qualities relevant for rubber and upland rice suitability have been determined based on the land characteristics. First, the importance of each land characteristic within a land quality has been estimated (e.g. fertility and fallow for soil fertility, in Table 4.8). Then the importance of each land quality compared to the other land qualities has been established (e.g. Table 4.10). The final weight of a land characteristic is the product between its weight within the land quality and the land quality weight (Appendices 11 and 12). When a land characteristic appeared in more than one land quality, i.e. slope or depth, the final weight of this land characteristic is the sum of the partial weights within land qualities (See Appendices 11 and 12). Examples of the pairwise comparison for fertility and workability for rice are given in tables 4.8 and 4.9. Appendices 9 abd 10 show the pairwise comparison for each land quality. Once obtained the weights for each land characteristic, the relative weights for land qualities were established.

Table 4. 8. Soil Fertility for rice

	Fertility	Fallow	Average
Fertility	1	2	0.67
Fallow	1/2	1	0.33

Table 4. 9. Workability for rice

	Slope	Texture	Fallow	Depth	Average
Slope	1	1/2	1/3	2	0.182
Texture	2	1	2	2	0.379
Fallow	3	1/2	1	2	0.302
Depth	1/2	1/2	1/2	1	0.138

In the case of upland rice, for workability fallow period was considered more important than slope and depth but less important than texture. This ranking for fallow was assigned taking into account that for the farmers this is the most important factor to be considered for rice cultivation. Using the same scheme, soil fertility was regarded as more important than rooting conditions, workability and erosion. The Pairwise Comparison Matrix for Land Suitability of upland rice is given in Table 4.10.

Table 4. 10. Pairwise Comparison Matrix for Upland Rice Suitability

	Soil Fertility	Moisture Availability	Rooting	Erosion	Workability	Accessibility	Average
Soil Fertility	1	2	1	5	5	5	0.30
Moisture Avail.	1/2	1	1	5	5	5	0.24
Rooting	1	1	1	5	5	5	0.27
Erosion	1/5	1/5	1/5	1	1/5	1/5	0.04
Workability	1/5	1/5	1/5	5	1	1	0.08
Accessibility	1/5	1/5	1/5	5	1	1	0.08

For rubber, rooting conditions, with soil depth as land characteristic, was considered more important than soil fertility. A depth at least of 1 meter is required for the roots to develop. Accessibility was regarded as not so important compared to the other parameters because once the rubber tree is planted farmers do not have to go periodically to take care of the crop (Table 4.11).

Table 4. 11. Pairwise Comparison Matrix for Rubber Suitability

	Soil Fertility	Moisture Availability	Rooting	Erosion	Workability	Accessibility	Average
Soil Fertility	1	1/2	1/5	5	1	1	0.11
Moisture Avail.	2	1	1	5	5	5	0.28
Rooting	5	1	1	5	5	5	0.34
Erosion	1/5	1/5	1/5	1	1/5	1/5	0.04
Workability	1/5	1/5	1/5	5	1	5	0.12
Accessibility	1/5	1/5	1/5	5	5	1	0.12

For each land characteristic a map was created. In the case of erosion and texture, where the data is ordinal or categorical, reclassified values were assigned (See Tables 4.12 and 4.13).

Table 4. 12. Reclassified Probability values for Observed Erosion

Erosion Observed	Membership value
No erosion observed	1
Low erosion observed	0.5
Moderated erosion observed	0.3
High erosion	0.1

Soil texture influences the moisture availability of the soil and its workability. Clays combined with loam or sand give good water retention. Sands and sandy loams retain less water, and dense and heavy clays give low water retention. Heavy clays are more difficult to work compared to other soils, mainly in the case of rice where the land has to be ploughed.

Table 4. 13. Reclassified Probability values for Soil Texture

Rice		Rubber	
Soil Texture	New value	Soil Texture	New value
L	0.8	L	0.8
SL	0.6	SL	0.7
LiC	0.9	LiC	0.9
CL	0.9	CL	1
HC	0.4	HC	0.6
R	0	R	0

The influence of fallow period in the study area was considered taking into account its influence on the crops. Fallow influences fertility and workability. In the case of rubber, where the requirements for fertility are not so strict, fallow contributes little to the soil performance; but for rice the fallow period can improve the soil fertility. Oppositely, a longer fallow period makes difficult the workability: it is required to remove the bushes and to burn them in order of preparing the land. These factors have been considered and introduced in a membership value, as can be seen in Tables 4.14 and 4.15.

Table 4. 14. Probability Values for Fallow Period Upland Rainfed Rice

Rice	Fertility	Workability		Membership
No fallow	0.2	1	0.44	0.4
Young fallow	0.5	0.7	0.56	0.6
Medium fallow	0.7	0.5	0.64	0.6
Old fallow	0.9	0.1	0.66	0.7
70% fertility, 30% workability				

Table 4. 15. Probability Values for Fallow Period Rubber

Rubber	Fertility	Workability		Membership
No fallow	0.3	1	0.58	0.6
Young fallow	0.4	0.9	0.6	0.6
Medium fallow	0.7	0.8	0.74	0.7
Old fallow	0.8	0.7	0.76	0.8
60% fertility, 40% workability				

4.5.2. Fuzzy Calculation

To obtain the fuzzy maps for land suitability it is required to calculate the convex combination of the raster values containing the different fuzzy parameters. The convex combination means that "if $A_1,\ldots A_k$ are fuzzy subclasses of the defined universe of objects X and $w_1,\ldots w_k$ are non-negative weights summing up to unity, then the convex combination of $A1,\ldots Ak$ is a fuzzy class A whose membership function is the weighted sum" (Burrough, 1989), where the weights $w_1,\ldots w_k$ were calculated using APH as described in the previous section and the fuzzy parameters μ_I have been calculated with the membership functions described in the previous sections and using conditional statements in ArcGIS (see Appendix 8). Equations 4.4 to 4.6 present the convex combination.

$$\mu_A = w_1 \cdot \mu_{A1} + ...w_k \cdot \mu_{A1}$$ Equation 4. 4

$$\mu_A = \sum_{j=1}^{k} w_j \cdot \mu_{Aj}(x) \qquad x \in X$$ Equation 4. 5

Where:

$$\sum_{j=1}^{k} w_j = 1 \qquad w_j > 0$$ Equation 4. 6

The process to obtain the land suitability evaluation based on fuzzy logic is summarized in figure 4.12. For each soil parameter a membership function or probability weight (in the case of texture and erosion) were used to create the respective fuzzy parameter. The fuzzy fertility was the combination of fuzzy nitrogen, fuzzy phosphorus, fuzzy base saturation, fuzzy cation exchange capacity and fuzzy organic matter. Once obtained the fuzzy fertility it was combined with the other fuzzy land characteristics (i.e. slope, depth, distance, texture, erosion and fallow). The weights were obtained through the Analytic Hierarchy Process AHP based on pairwise comparisons.

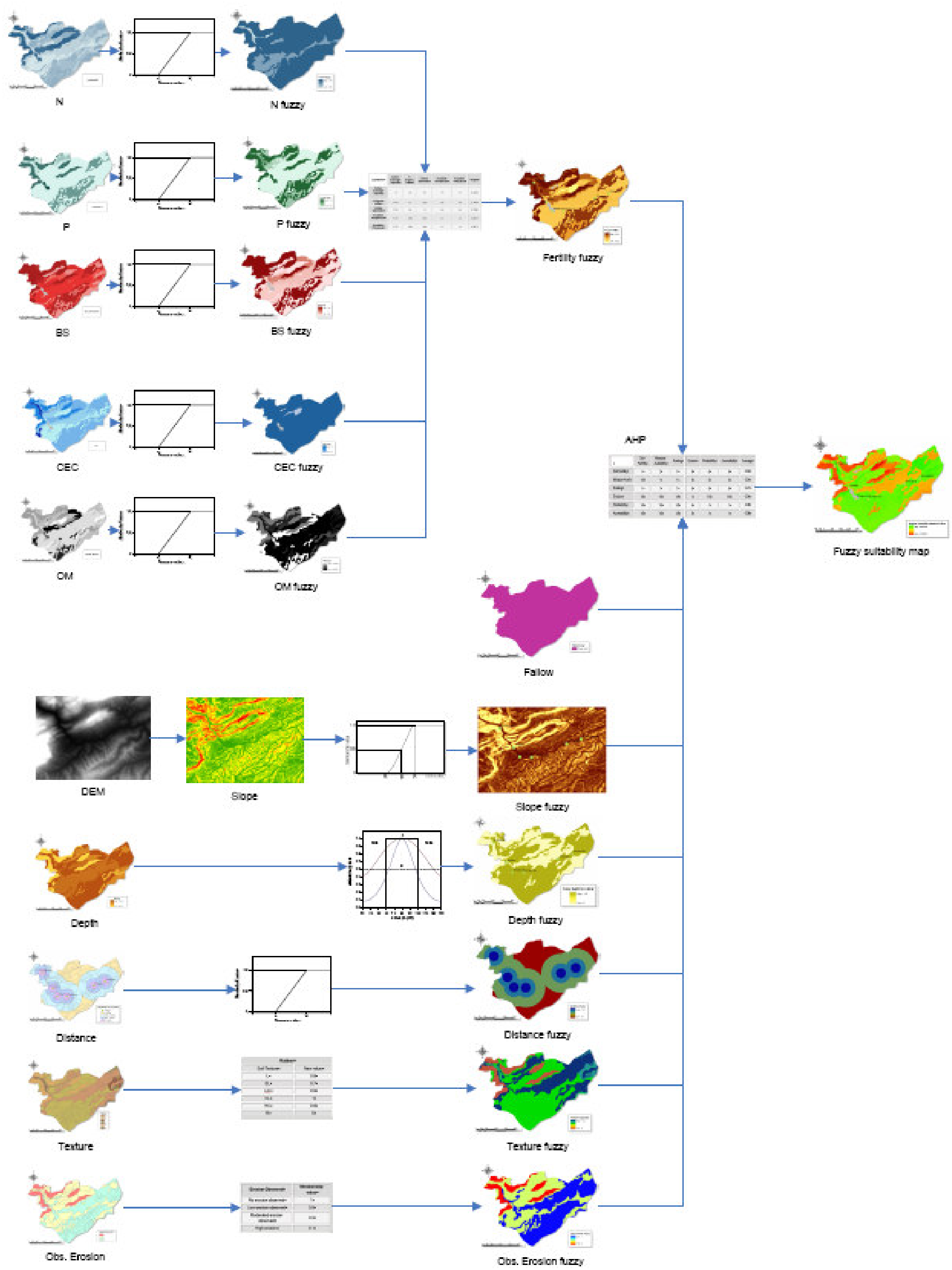


Figure 4. 12. Fuzzy process for land suitability.

4.6. Maps Comparison

4.6.1. Maps Combination

The resulting maps from ALES (Boolean evaluation), fuzzy modelling and the farmers' perception were compared on a cell by cell basis. Each map was rasterized using a 5m x 5m cell size. To perform the comparisons, the fuzzy suitability maps were reclassified into 4 classes (corresponding to the four suitability classes) using the natural breaks from the histograms. To determine the correspondence between the raster maps they were combined: an option is to use the Combine function in ArcGIS, which assign for each cell in a raster its correspondent value from the other raster including the number of appearances of each combination. A different option but based on the same principle is to multiply one raster by 10, so the four classes of this map become 10, 20, 30 and 40. Then the classes from the second raster map are added to the first raster. Values such as 11, 22, 33 and 44 represent correspondence between cell values from both maps. The number of appearances is used to create similarity matrices.

4.6.2. Kappa Statistic

To assess the agreement between two maps, the *kappa* statistic was calculated. The *kappa* statistic was developed by J. Cohen (1960) to compare two different psychiatric diagnoses. The *kappa* statistic is a measurement of how the degree of agreement between two observations is given by chance, and its calculation is based on the difference between observed agreement and expected agreement. A kappa value of 0 indicates that there is a poor agreement between the maps, in other words, they are not related. A value of 1 indicates an almost perfect agreement; a value less than 0 indicates no agreement above that the expected by chance; a value of -1 represents complete disagreement (Rossiter 2004).

4.6.3. Agreement Maps

The grade of agreement between land suitability classifications has been mapped using colours: green corresponds to agreement between the areas classified in both maps, yellow represents a level of disagreement (i.e. S1 classified as S2 in one map, or S2 classified as S3); orange represents two levels of disagreement (i.e. S1 classified as S3); and red detonates areas completely misclassified (i.e. any suitable class S classified as N).

5. RESULTS AND DISCUSSION

5.1. Results

5.1.1. Farmers' Soils and Suitability Map

The classification given to the soils by the farmers is based on colour and texture composition, being the former the most important aspect for soils identification. The suitability of a crop is related to the type of soil as well to the number of years the plots have been in fallow conditions. According to the farmers more fallow years can increment the number of times the soil can be used and then the yield production.

Figure 5.1 shows the suitable areas for upland rice and rubber according to the farmers' perception. Areas in red were classified as suitable for other types of crops, which does not mean necessarily that those units are unsuitable for rubber or rice; instead these areas may be suitable but are not used for rubber or rice at the moment.

In the *Kum Ban* area there is a lack of knowledge about rubber, and farmers rely on the information provided by relatives or friends who are cultivating rubber in other areas. Table 5.1 summarizes the total amount of areas suitable according to the farmers.

Farmers' suitability for upland rice

Farmers' suitability for rubber

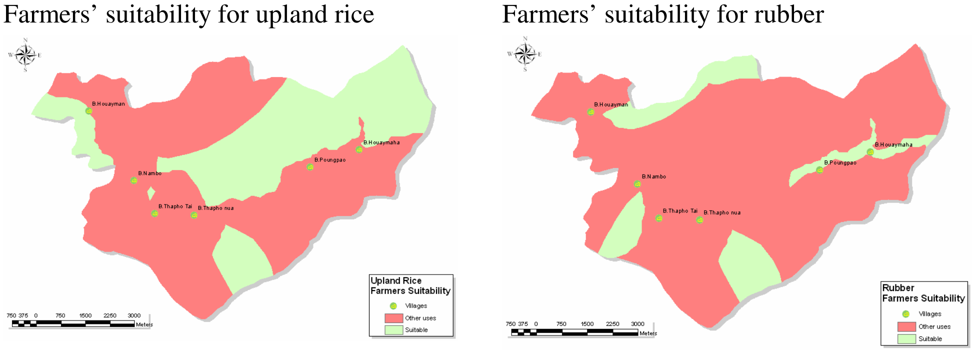


Figure 5. 1. Farmers' suitability for upland rice and rubber.

Table 5. 1. Farmers' Suitability Results for Upland Rice and Rubber

Upland Rice

	Area	%
Suitable	2097.9	37
Not defined	3572.1	63

Rubber

	Area	%
Suitable	793.8	14
Not defined	4876.2	86

5.1.2. Land Suitability based on Boolean Theory

Figure 5.3 shows the results of land evaluation obtained with ALES. According to the crisp and fuzzy models, the optimal condition for rubber and upland rice is given with a medium fallow (2 to 4 years). During this period of time the soil will recover its nutrients and a better yield may be produce, this is particularly valid in the case of upland rice, where soil fertility can be a main constraint. In the case of rubber, fallow influences the initial workability of the soil and may increase the fertility, but rubber can grow in low fertility soils and does not require high levels of maintenance.

For all the different types of fallow period considered, 12% (680.4 ha) of the total study area is not suitable for upland rice cultivation; 88% of the total study area (4,890 ha), is somehow suitable for upland rice. For different fallow periods the percentage of area moderately suitability for upland rice varies, being 61%, 49% and 48% of the total area for no fallow, medium fallow and old fallow respectively. It has to be taken into account that the fallow period alone does not change the suitability but the way the different land characteristics interact within the suitability matrices and decision trees of the model. Figure 5.2 shows the percentages of the total area.

It can be noticed that no fallow provides a better suitability for upland rice than a medium or old fallow period; this result has to do with the constraint that fallow gives to workability: a medium or old fallow period implies more work in order to prepare the land.

Upland Rainfed Rice | Rubber

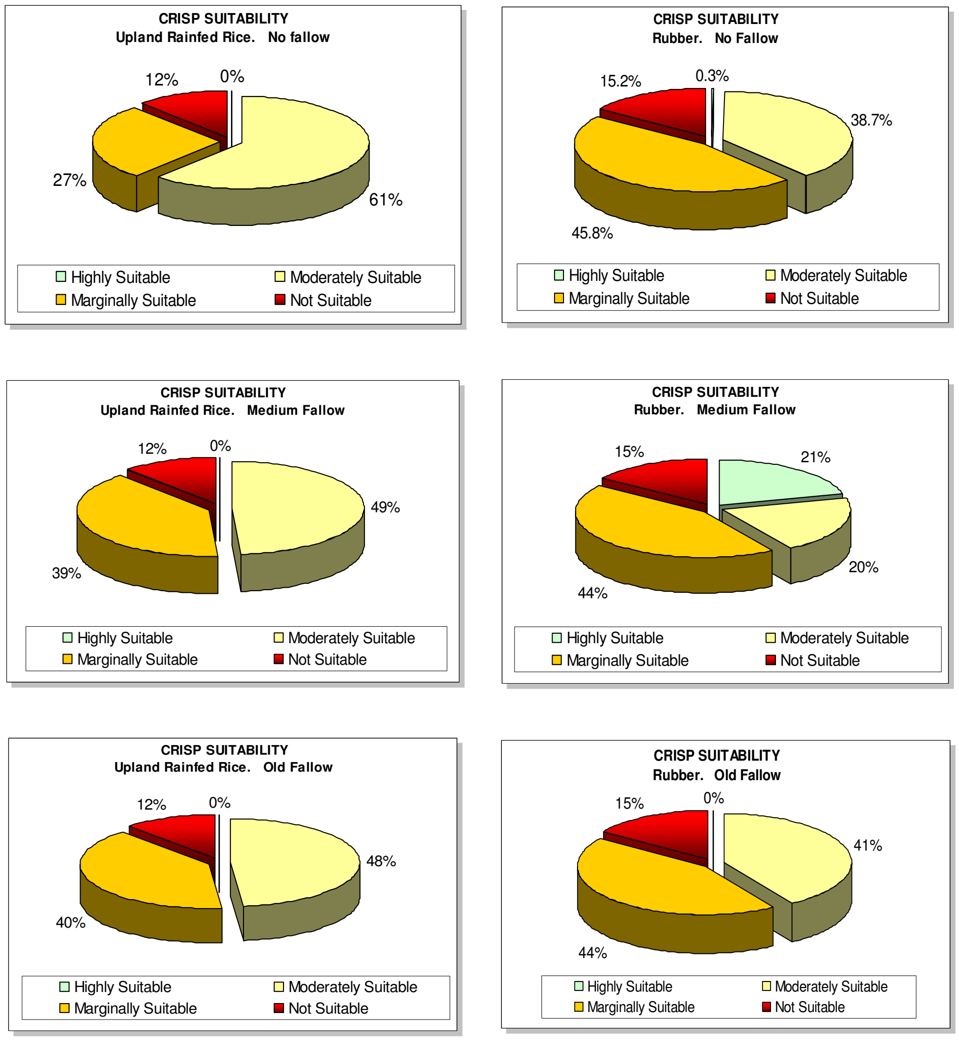


Figure 5. 2. Upland rice and rubber suitability under Boolean theory: suitability in percentage of the total area.

From Figure 5.2 it can be noticed that the fallow period decreases the moderately suitable areas for upland rice due to workability. In the case of rubber the optimal condition is given with a medium fallow, where there seems to be an equilibrium between workability and improvement of the soil fertility.

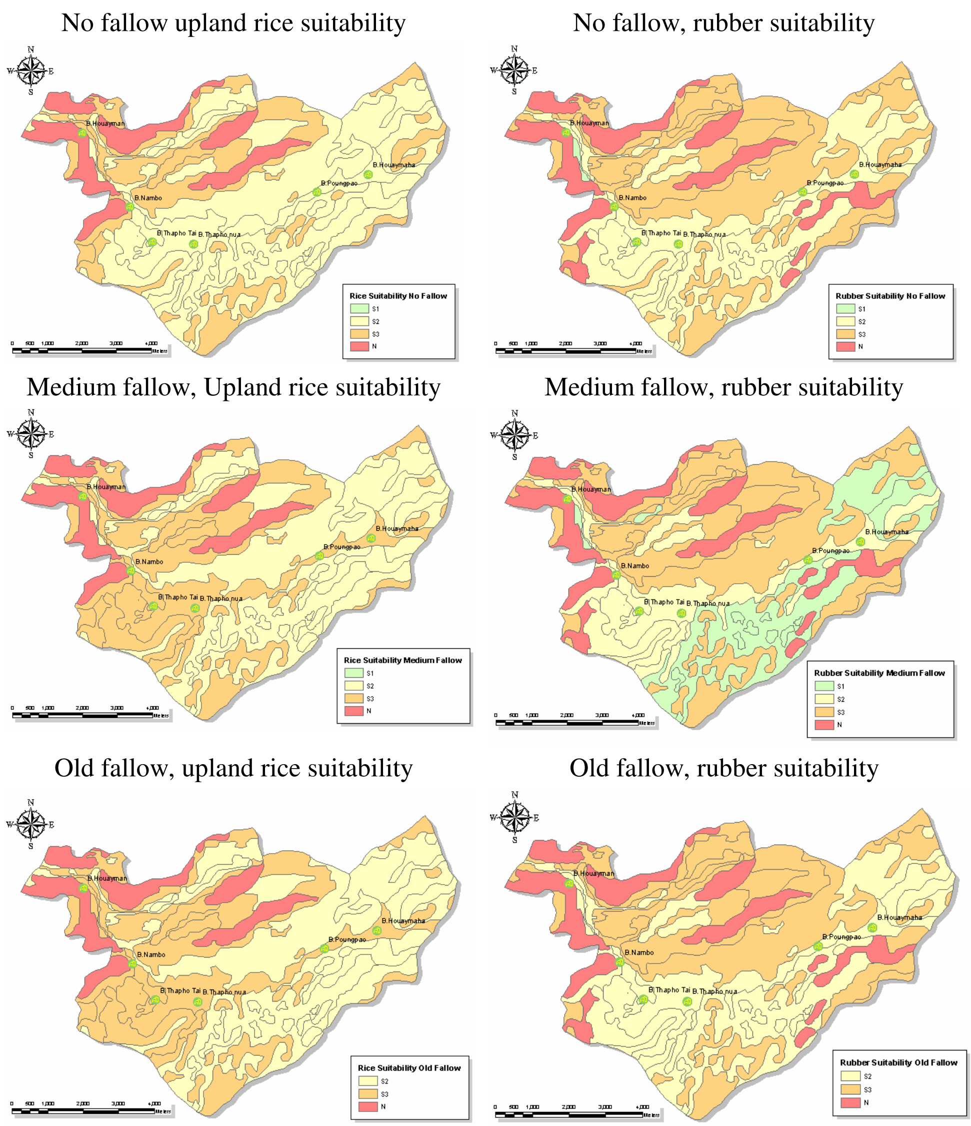


Figure 5. 3. Land Suitability for upland rice and rubber based on Boolean Theory.

5.1.3. Land Suitability based on Fuzzy Theory

The fuzzy based classification shows that 88% of the total study area falls within a certain suitability class, which is about the same area as in the Boolean classification. In the fuzzy classification the suitability is given between 0 and 1, being 1 a highly suitable area and 0 a not suitable one. With the fuzzy approach it is possible to find highly suitable areas both for upland rice and rubber with membership values between 0.88 and 0.91 for upland rice and between 0.95 and 0.97 for rubber (see Appendix 17). The reclassified values for the fuzzy model are shown in Figure 5.6.

After reclassifying the suitability values based on natural breaks of the raster histogram, four defined classes were obtained, judged to correspond to the four suitability classes S1, S2, S3 and N. Figure 5.4 shows the natural breaks for the histogram for upland rice with no fallow period. From the fuzzy results, it was found that the total area suitable for upland rice is 88%, with a 50% highly suitable. In the case of rubber the total area suitable is 88% as well, but only 24% is highly suitable. Figure 5.5 presents the suitability in percentages of the total area for upland rice and rubber. Due to the similitude of results for different fallow periods only the medium fallow results are shown.

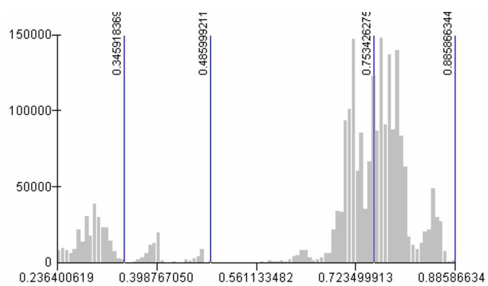


Figure 5. 4. Histogram with natural breaks for fuzzy-based classification for upland rice, no fallow period.

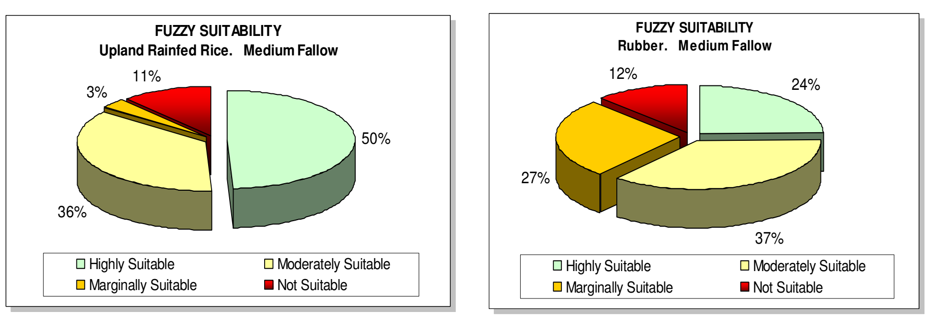
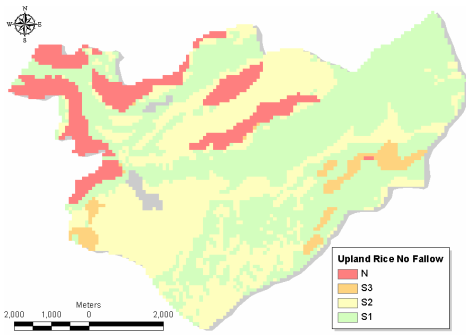
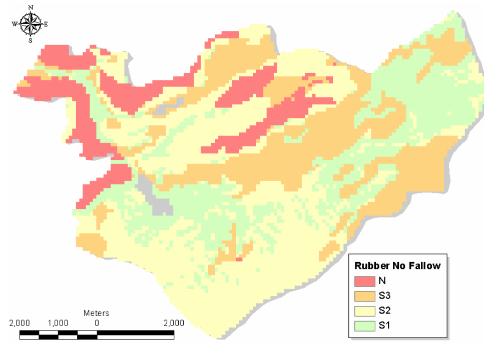


Figure 5. 5. Upland rice and rubber suitability under Fuzzy theory: suitability in percentage of the total area.

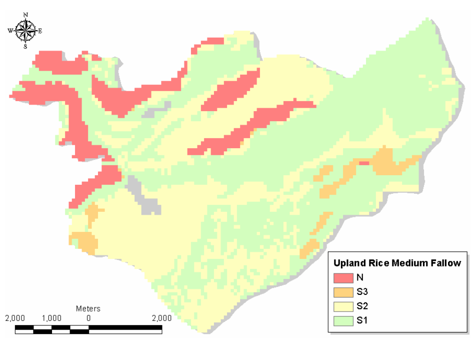
Rice suitability No fallow



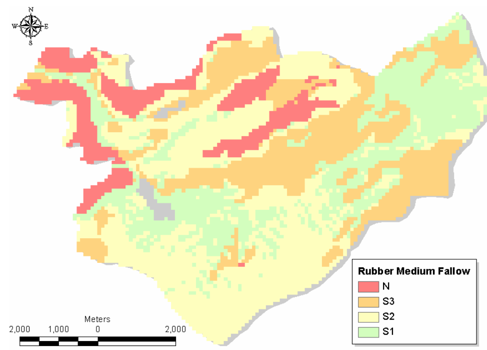
Rubber suitability, Old fallow



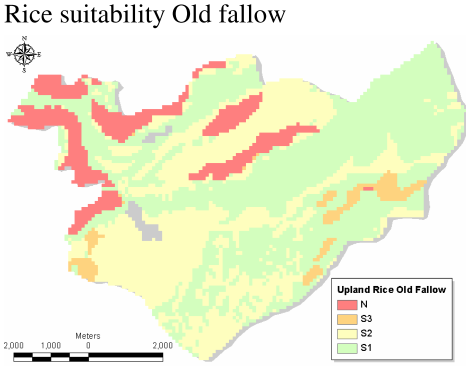
Rice suitability Medium fallow



Rubber suitability, Medium fallow



Rice suitability Old fallow



Rubber suitability, No fallow

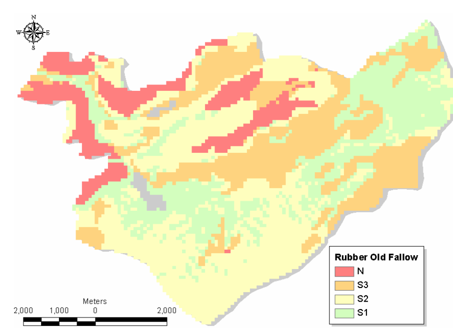


Figure 5. 6. Land Suitability for upland rice and rubber based on Fuzzy Theory.

5.1.4. Summary of Boolean and Fuzzy Results

Tables 5.2 and 5.3 summarize the results of suitability for different fallow periods and for the Boolean and fuzzy models. It has to be noticed that the area in the fuzzy model is 5,570 ha while for the crisp model is 5,670, due to two soil units that were not analysed under the fuzzy theory because no information on soil laboratory results was available for them.

Table 5. 2. Suitability Results for Upland Rainfed Rice

FALLOW PERIOD	NO FALLOW				MEDIUM FALLOW				OLD FALLOW			
SUITABILITY	CRISP		FUZZY		CRISP		FUZZY		CRISP		FUZZY	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Highly Suitable	0	0	2729.3	49	0	0	2835.0	50	0.0	0	2778.3	49
Moderately Suitable	3458.7	61	2005.2	36	2778.3	49	2041.2	36	2721.6	48	2041.2	36
Marginally Suitable	1530.9	27	167.1	3	2211.3	39	170.1	3	2268.0	40	170.1	3
Not Suitable	680.4	12	668.4	12	680.4	12	623.7	11	680.4	12	680.4	12

Table 5. 3. Suitability Results for Rubber

FALLOW PERIOD	NO FALLOW				MEDIUM FALLOW				OLD FALLOW			
SUITABILITY	CRISP		FUZZY		CRISP		FUZZY		CRISP		FUZZY	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (Ha)	%	Area (ha)	%
Highly Suitable	17.0	0.3	1336.8	24	1190.7	21	1360.8	24	0.0	0	1360.8	24
Moderately Suitable	2194.3	38.7	2060.9	37	1134	20	2097.9	37	2324.7	41	2097.9	37
Marginally Suitable	2596.9	45.8	1503.9	27	2494.8	44	1530.9	27	2494.8	44	1530.9	27
Not Suitable	861.8	15.2	668.4	12	850.5	15	680.4	12	850.5	15	680.4	12

5.2. Discussion

The structure of the land suitability evaluation in the FAO framework makes the assessment rigorous. Only one low parameter is enough to reduce the suitability from high to moderately suitable or not suitable, even if the relevance of this parameter is lower compared to the others. The selection of land characteristics, their limits, and how they interact within the decision trees is a sensitive issue when performing the evaluation. This makes the inclusion of parameters such as workability or distances, that may have less relative importance for the physical suitability, decisive for the final result of the evaluation. A plot that physically is suitable (S1) may be reduced in class (to S2, for instance) or in order (to N) if it is located too far away from the villages or if it is difficult to work on it.

In Figure 5.2 it can be noticed that there are no land units classified as highly suitable for upland rice; these results have to do with the way the different parameters interact under a Boolean logic. Even if all the parameters that govern the suitability have a ranking of S1 but a single parameter is ranked as S2, the whole suitability is reduced. In the traditional land evaluation, all the parameters have the same weight which makes the classification quite strict. An alternative to solve this problem is to assign different weights to the land characteristics according to their importance for the suitability, but the potential complication is that the same land characteristic may appear for different land qualities and with different weights.

For fertility, NAFRI assigned values for each soil unit based on cation exchange capacity (CEC), base saturation (BS), nitrogen, phosphor and percentage of organic matter. When CEC or BS parameters were not available (soil units CMe-D-CL-a(M) and CMe-D-HC-a(M)) NAFRI employed pH, nitrogen and phosphor to determine the fertility and, for these particular soil units, assigned a medium fertility class (M). In the fuzzy calculation, actual values of cation exchange capacity and base saturation were employed. Because the soil units mentioned above do not have that information these areas have No Data and the suitability was not calculated.

The results of land suitability under the Boolean theory show that 86% of the area is suitable for rice, while the farmers classified 37% of the total area as suitable for upland rice. This difference has to do with preferences for cultivation, tradition and current conditions of the plots. Certain areas are preferred for traditional cash and subsistence crops such as jobs tear, soy bean, teak, sesame among others.

Fallow was introduced in the models as a land characteristic that affects workability and fertility, but there is not certainty on how is the exact impact on these land qualities. In this study the inclusion of fallow has been made based on assumptions made according to the information provided by the farmers, which may not be accurate.

Under the fuzzy theory, the results for different fallow periods had very small variations. The overall weight of fallow compared to the other land characteristics is around 10%; a no fallow period has a probability membership value of 0.6 and an old fallow period a probability membership value of 0.8. In the fuzzy model the suitability has been discriminated based on the histogram breaks of the cell groups, in this way it was possible to define highly suitable areas even if the maximum value was 0.88 instead of 1 (e.g. upland rice, no fallow).

The main constraint for rubber is the soil depth. Most of the study area has steep slopes with a soil with depths below 1.00m, which is the optimal depth required for rubber rooting. Rice has a constraint the soil fertility, which is not optimal for more than 85% of the study area (only 837 ha from 5670 ha with high fertility according to NAFRI classification, 2002).

As a main advantage of the Boolean theory, it is possible to control and trace easily which factors are affecting the suitability of a plot, while with the fuzzy model it is necessary to review the interaction between membership functions and weights, which is not a straightforward process. Fuzzy theory allows intermediate possibilities of suitability beyond the traditional classes given by the Boolean methods, but on the other hand it can over estimate the potential of a land. Oppositely, the Boolean theory can underestimate the real potential of a plot. In this sense, perhaps the land evaluator has to try with both theories and check with information on the field which one agrees better with the reality.

5.3. Comparison of Results

The Boolean suitability maps were rasterized and compared on a cell by cell basis with the fuzzy suitability maps results. Similarity matrices were created to determine the relative performance of the fuzzy results regarding to the Boolean suitability. The matrices indicate the number of cells compared for each class. In the same way, the farmers' suitability maps were rasterized (5x5m cells) and compared to the fuzzy and the crisp suitability maps. Appendices 13 to 16 include all the similarity matrices created. For the comparison with the farmers' classification, the suitability classes S1, S2 and S3 have been aggregated as a class 1. Disaggregated comparisons were made only for farmers' rubber classifications to assess the results against highly suitable plots.

In the matrices, the *kappa* statistic represents the agreement between the maps and the agreement between classes of both maps; the areal difference represents the proportion of overestimation or underestimation of a class in one map respect to the same class in the other map; the producer accuracy and user accuracy represents the percentage of agreement of one map respect the other; the mean accuracy is a combination of both producer and user accuracy; the parameter *d* represents the sum of correctly classified points; the parameter *q* is the sum of the products between correctly classified points and the total number of cells for each class; N is the total number of cells compared; and the overall accuracy indicates the general correspondence between the two maps as a whole.

5.3.1. Boolean and Fuzzy Suitability

Table 5.5 shows the results of the comparison for rubber with medium fallow period. Appendix 13 includes all the agreement matrices between crisp and fuzzy classification for rubber and upland rice under different fallow period conditions.

For upland rice with no fallow period the overall accuracy for the fuzzy map compared to the Boolean map was 31.8% (Appendix 13, Table A13.1). This result is due, among other reasons, to the lack of class 1 -highly suitable areas- in the Boolean map. From the *kappa* values it can be seen that only the class 4, not suitable areas, has a high probability of not being classified randomly. The areal difference (over estimation or under estimation of an area) shows for the class 4 a high agreement (0.2, the areas correspond) while for the other classes the differences are high, particularly for class 3 where the areal difference is 87% (overestimation). The results for medium fallow and old fallow show an overall accuracy of 18.4% and 18.3% respectively, with very low *kappa* values, of -2.5% and -2.3% (See Appendix 13)

Table 5. 4. Similarity Matrix for Rubber. Boolean vs. Fuzzy classifications. Medium Fallow Period.

ALES SUITABILITY	FUZZY SUITABILITY						Total
	Class	0	1	2	3	4	
	1	204	245398	203296	12992	792	462682
	2	120	221625	219510	8376	1707	451338
	3	0	69509	383618	498977	23056	975160
	4	0	5435	12923	73676	246661	338695
	Total	324	541967	819347	594021	272216	2227875
Producer Accuracy		-	45.3	26.8	84.0	90.6	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
1	43.9	48.9	97.2	245398	2.5E+11	30.94
2	48.6	34.5	-81.5	219510	3.7E+11	8.19
3	51.2	63.6	39.1	498977	5.8E+11	71.54
4	72.8	80.8	19.6	246661	9.2E+10	88.93

Overall Accuracy	Kappa (%)	d	q	N
54.3	38.3	1210546	1.3E+12	2227875

In the case of rubber with a medium fallow period, the overall accuracy obtained for the fuzzy map when compared to the Boolean map was 54%, with a *kappa* statistic of 0.38. The overall accuracy for no fallow and old fallow periods was 52.1% and 52.4% respectively with *kappa* statistic values around 0.33. It can be noticed a better performance for the fuzzy map in the case of rubber when compared to the fuzzy maps created for upland rice: the *kappa* values are higher (0.31 for class 1, 0.715 for class 3) with exception of the class 2, moderately suitable (0.8). On the other hand, the areal differences are quite big, which means that more area has been assigned to the classes from the fuzzy model in relation to the Boolean model for classes 1 and 3; for class 2 there is an underestimation of the area, therefore there is not high coincidence between the four classes between the maps. The best correspondence appears again for class 4, not suitable areas.

Figure 5.7 shows the correspondence between results. The left side graph presents the number of cells from the Boolean classification (y axis) in different suitability levels of the fuzzy classification (x axis). Oppositely, the right side graph presents the number of cells from the fuzzy classification within the suitability levels of the Boolean map. From the graph it can be observed that what in the fuzzy map corresponds to highly suitable areas, for the Boolean map corresponds mainly to moderately suitable areas. On the other hand, most of the cells classified as highly suitable within the fuzzy map, correspond to moderately suitable areas in the Boolean map.

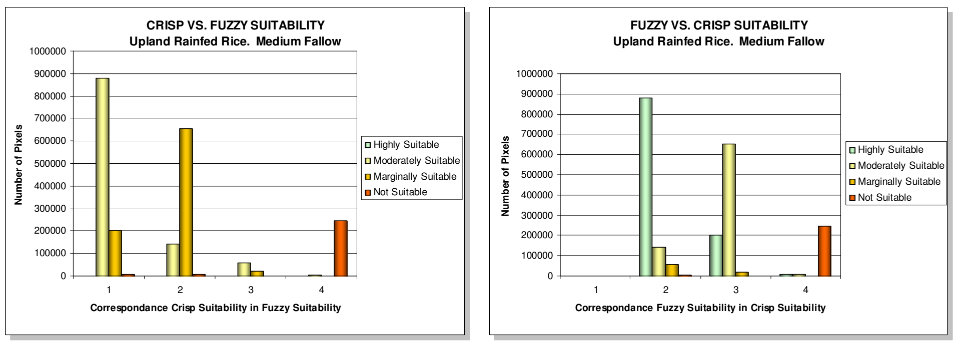


Figure 5. 7. Correspondence between Boolean and Fuzzy results for upland rice with medium fallow.

Figure 5.8 presents maps with the correspondence of classes for both maps. Areas in green represent areas where the classification coincides, while areas in red are those were there was not correspondence. Orange and yellow colours represent areas with one and two levels of difference respectively, e.g. highly suitable areas (S1) classified as moderately suitable (S2) or highly suitable areas (S1) classified as marginally suitable (S3). If a marginally suitable area was classified as not suitable the result is considered as without correspondence.

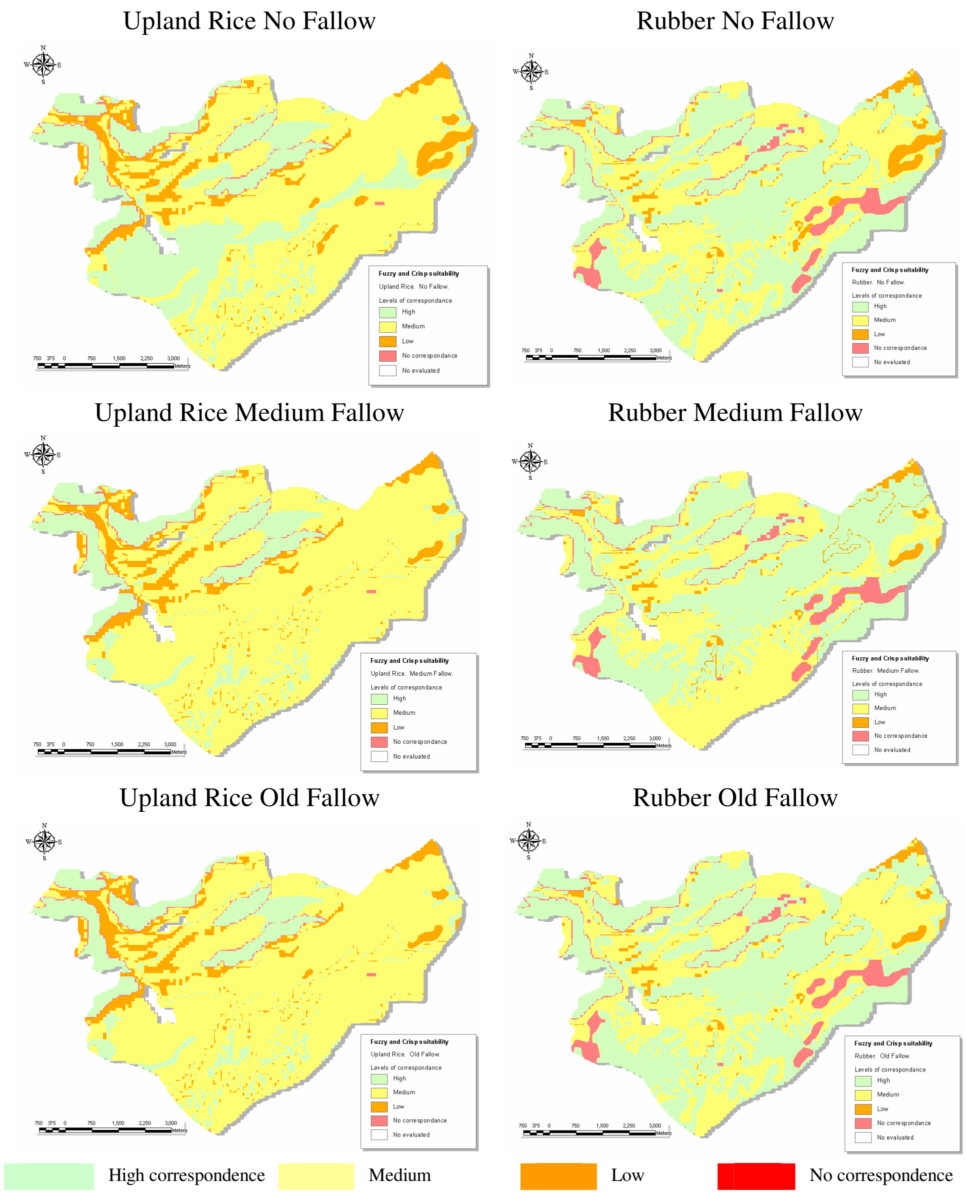


Figure 5. 8. Maps with correspondence between fuzzy and crisp results.

The Boolean and fuzzy classifications of rubber present a better correspondence when compared to the classifications for upland rice, but this similitude is given due to the not suitable areas in both maps, were soils depth is a clear constraint for rubber.

5.3.2. Farmers and Crisp Suitability

The results of the comparison between farmers' suitability maps and the Boolean classification for upland rice and rubber are summarized in the Appendix 16. Areas classified as suitable by the farmers (value 1) have been compared to the three suitability classes (S1, S2 and S3) as an aggregated class 1, while the other areas (value 0 in farmers' class) were compared to the not suitable areas (N) as a class 0. For upland rice, the overall correspondence between Boolean suitability areas and farmer's classification is 38% for the different fallow periods, with a very low and negative kappa of -0.03 (Tables A16.1 to A16.3). The distribution of the farmers' suitability within the Boolean model and the Boolean classes within the farmer's suitability for upland rice can be observed in Figure 5.9. The left side graph indicates that the farmers mainly classified as suitable areas regarded as moderately suitable according to the Boolean theory, while the right side graph shows that most of the suitable areas according to the Boolean classification (S2 and S3) were not considered as suitable for upland rice by the farmers.

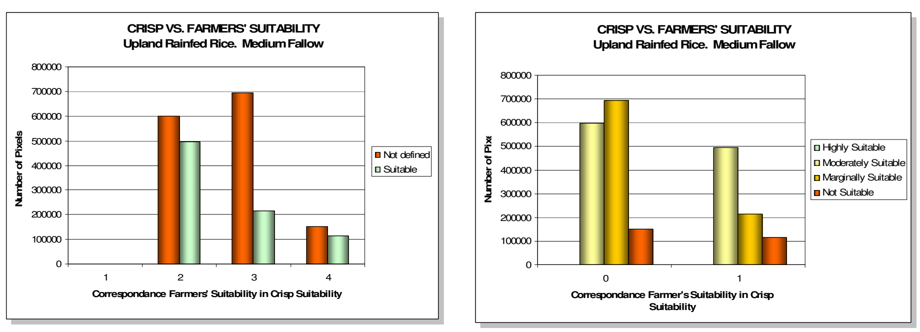
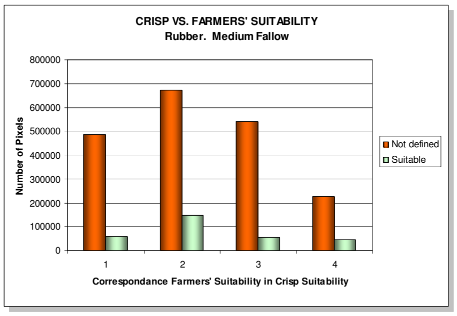


Figure 5. 9. Correspondence between Boolean and Farmers' results for upland rice with medium fallow.

For upland rice under the Boolean theory highly suitable plots were not found, and then the correspondence of suitability with the farmers' perception had to be compared with the other suitability levels. From the classification made by the farmers, 86% of the plots defined as suitable falls within a suitable area (S2 or S3) where 60% corresponds to the moderately suitable areas (S2).

For rubber the classification made by the farmers has an overall agreement of 24%. for no fallow period and old fallow period, and an overall agreement of 22% for medium fallow (Tables A16.4. to A16.6 in Appendix 16). The distribution of the farmers' classification within the Boolean suitability can be seen in Figure 5.10.



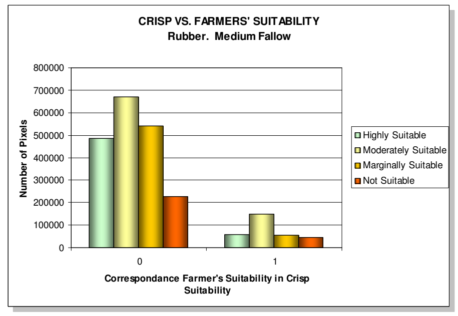


Figure 5. 10. Correspondence between Boolean and Farmers' results for rubber with medium fallow.

From Figure 5.10 it can be noticed that the farmers classified as suitable for rubber areas classified as suitable (S1, S2 and S3) and not suitable by the Boolean theory. The right side graph shows that most of the suitable areas were not classified by the farmers.

The correspondence maps between farmers' suitability maps and the Boolean and fuzzy classifications are presented in Figure 5.11. Areas in red represent not suitable areas classified by the farmers as suitable.

From the total area classified by the farmers as suitable for upland rice, 14% falls within not suitable areas according to the Boolean which is equivalent to 290 ha; in the same way, 15% of the area classified by the farmers as suitable for rubber, equivalent to 120 ha, falls into not suitable areas.

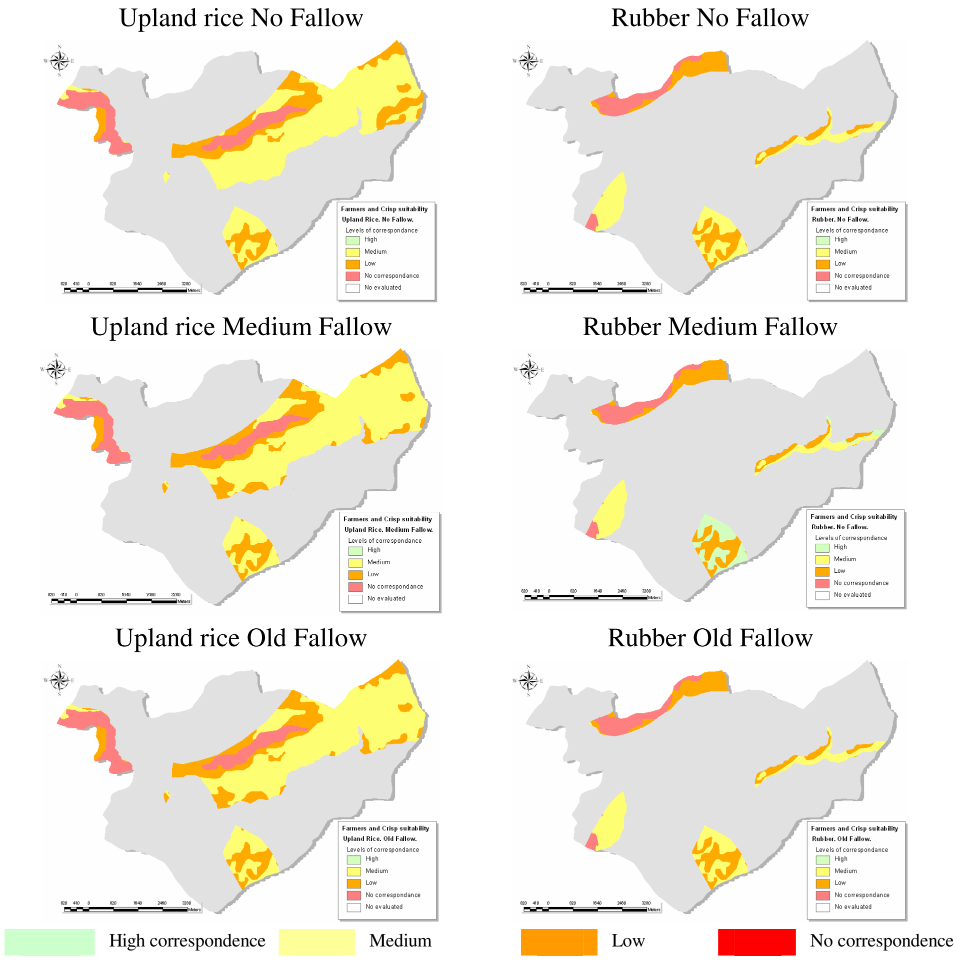


Figure 5. 11. Comparison maps of farmers and Boolean suitability.

5.3.3. Farmers and Fuzzy Suitability

The results of the comparison between farmers' and fuzzy suitability classes can be seen in Appendices 14 and 15. Appendix 15 presents the results for the suitable classes S1, S2 and S3 aggregated as a single class 1. The comparison between fuzzy suitable areas (S1, S2, S3) and farmers' suitable areas (class 1) gives an overall agreement for rubber of 22% for the different fallow periods (Tables A15.4 to A15.6) and of 38% for upland rice.

When the suitability classes S1, S2 and S3 from fuzzy classification are compared to the suitable areas given by the farmers, 42% of the area classified by the farmers as suitable for upland rice corresponds with the fuzzy suitability classes (producer accuracy, in tables of Appendix 14). The *kappa* statistic remains low, 0.23 for the class 1 and 5% for the whole classification.

Figure 5.12 shows the distribution of cells for the areas classified by farmers as suitable for upland rice within the fuzzy suitability classes, and the fuzzy suitability areas within the farmers' classification. It can be noticed that areas potentially suitable for rice were not classified by the farmers and that 14% of not suitable areas according to the fuzzy model were classified as suitable by the farmers.

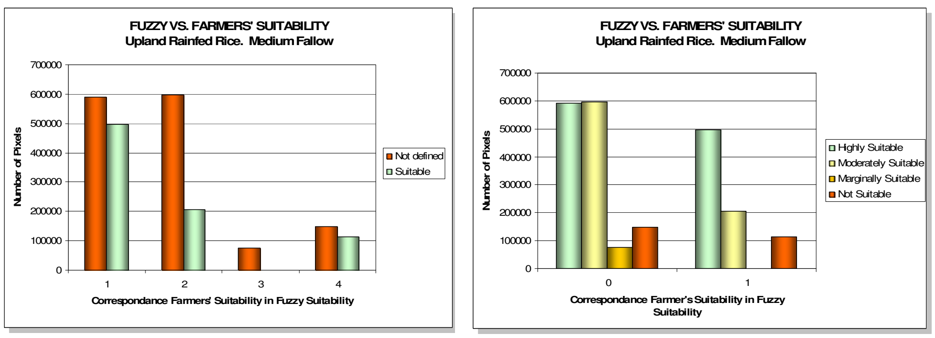


Figure 5. 12. Correspondence between Boolean and Farmers' results for rubber with medium fallow

In Appendix 14, Tables A14.4 to A.14.6 show the similarity matrices between fuzzy and farmers' classification for rubber. In these tables areas classified as suitable by the farmers (class 1) have been compared with the highly suitable areas in the fuzzy classification (S1). The aggregated values (classes S1, S2 and S3 against class 1, in Tables A15.4 to A15.6 in Appendix 15) show an overall agreement of 22% for the different fallow periods, with a very low *kappa* of -0.01.

Figure 5.13 shows the cells distribution of the farmers' classification within the fuzzy suitability classes and fuzzy classification within the farmers' classes. Because only 14% of the total study area was classified for rubber by the farmers, several suitable areas felt into class 0 (not classified).

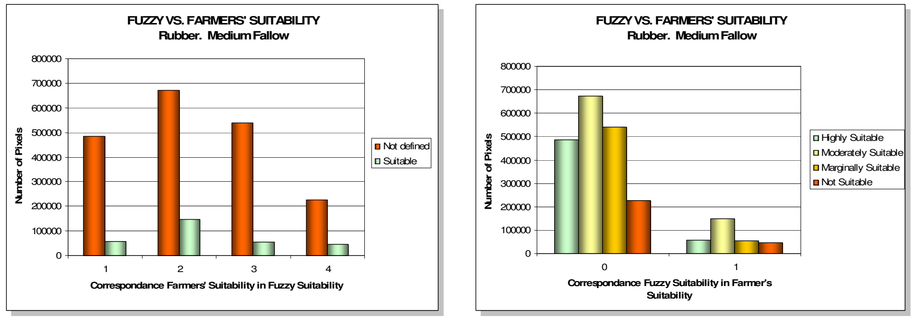


Figure 5. 13. Correspondence between Fuzzy and Farmers' results for rubber with medium fallow

The equivalence between the farmers' and the fuzzy classification is depicted in Figure 5.14. Green areas show high correspondence between suitability classes while areas in red represent not suitable areas classified as suitable.

5.3.4. Results Summary

Table 5.5 summarizes the results for the comparison between the models for different fallow periods. It can be seen that the best agreement was obtained for the medium fallow period for rubber, between the fuzzy and Boolean models (54% agreement, kappa 0.38).

Table 5. 5. Summary of comparisons results

MODELS	SUITABILITY	NO FALLOW		MEDIUM FALLOW		OLD FALLOW	
		Kappa	% Agreement	Kappa	% Agreement	Kappa	% Agreement
Boolean vs. Fuzzy	Upland Rice	0.10	31.8	-0.03	18.4	-0.02	18.26
	Rubber	0.33	52.1	0.38	54.3	0.33	52.4
Boolean vs. Farmers	Upland Rice	-0.03	35.4	-0.03	35.4	-0.03	35.4
	Rubber	-0.01	23.9	-0.01	21.7	-0.01	23.9
Fuzzy vs. Farmers	Upland Rice	-0.30	38.2	-0.30	38.2	-0.30	38.2
	Rubber	-0.10	21.7	-0.10	21.7	-0.10	21.7

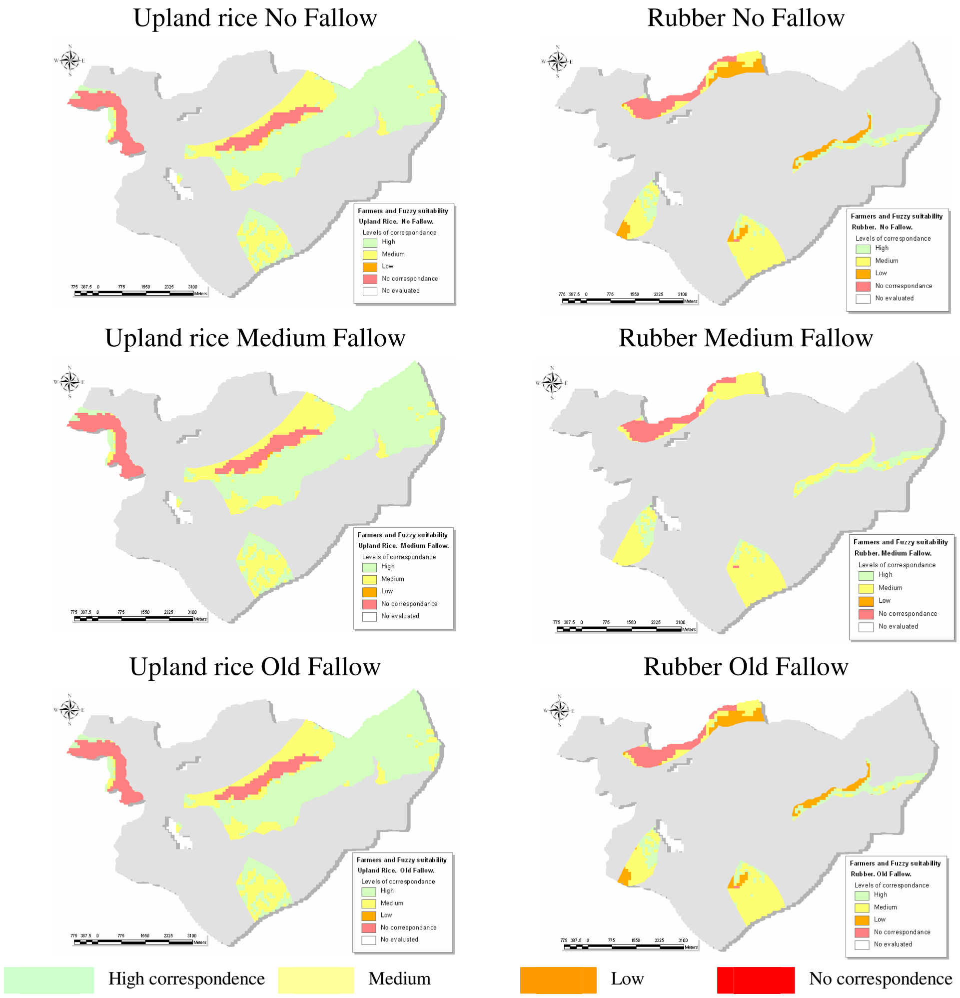


Figure 5. 14. Comparison maps of farmers and Fuzzy suitability.

5.3.5. Discussion of Comparisons Results

The fuzzy and the Boolean classifications differ mainly due to the suitability reclassification of the fuzzy maps. For instance, upland rice has a maximum membership value of 0.88 so the highly suitable areas have this value as a maximum limit. In other words, in fuzzy an area can be classified as S1 with a membership value that is not so close to 1, while in the Boolean theory it is required that all the parameters for that soil unit have a value of 1.

It seems that farmers have identified areas suitable for rubber based on the current cultivations in the area, and on expectations more than on experience. For both land utilization types the farmers classified as suitable areas that according to the fuzzy and crisp model are not suitable.

The low correlation between the farmers' suitability classes for rubber and the fuzzy and Boolean models may have an explanation on the lack of knowledge of the requirements for this land utilization type. In the study area farmers are cultivating rubber either supported by SIDA or by their own initiative. No yield has been produced yet and the oldest trees are around three years old. It is possible that rubber is being planted in areas not suitable having as result the atrophy of the seedlings or a very low yield in case the trees grow enough. The lack of experience on rubber may result as well in the wrong selection of rubber species for the area and difficulties harvesting the latex (NAFRI, 2005).

In the Boolean classification, the absence of class 1 (S1, highly suitable areas) reduces the agreement when comparisons are made between the farmers' and the fuzzy classifications. The low *kappa* values in the comparison between Boolean and farmers classes (-0.65, Appendix 16) indicates that there is no agreement between the maps, and the areas with agreement are given by chance. The comparison of classes S2 and S3 with the farmers' class 1 for upland rice gives an agreement of 35% because class S1 is excluded.

One of the main constraints of the maps created by the farmers is that only two classes were identified: suitable for upland rice or rubber and suitable for other cultivations. In the comparison using similarity matrices, the areas classified as suitable by the farmers have been considered as highly suitable while the other areas as not suitable, which may not be accurate; this single classification also causes the disagreement between the suitability maps. Because in the Boolean classification highly suitable areas were not frequent the comparison with the farmers' classification resulted in low correspondence. On the other hand, using the fuzzy theory highly suitable areas were found for both land utilization types, and the comparison with the farmers shown a better correspondence.

5.4. Potential Land Suitability Classification

The potential suitability for upland rice and rubber has been evaluated according to the Boolean theory using ALES. The land qualities and land characteristics employed were the same as in the previous models, but land qualities with a restrictive effect such as accessibility and erosion have been assumed as with optimal conditions. For this model slope still remains a constraint for accessibility. Assuming that the distance is not a restriction means that the plots are located close to the farmers' houses. The results from the evaluation can be seen in Figure 5.15 and Table 5.6.

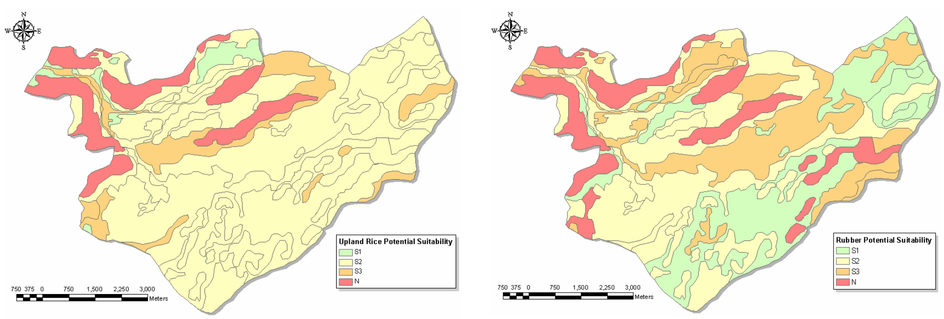


Figure 5. 15. Potential land suitability classification for upland rice (left) and rubber (right)

Table 5. 6. Potential suitability for Upland Rice and Rubber

Upland Rice (No fallow)

Suitability	Area (ha)	%
S1	156	2.8
S2	4229	74.6
S3	621	11.0
N	664	11.7
Total:	5670	100.0

Rubber (Medium fallow)

Suitability	Area (ha)	%
S1	1386	24.4
S2	2095	36.9
S3	1330	23.5
N	859	15.1
Total:	5670	100.0

For upland rainfed rice, the best potential condition is given for a no fallow period. In the model, workability is related to fallow; workability in the Boolean model decreases suitability from moderately suitable to marginally suitable for upland rice and from highly suitable to moderately suitable for rubber.

5.5. Accuracy and Sources of Error

The Boolean and Fuzzy land suitability evaluations carried out for this study rely on the input data provided by NAFRI. The soils map stored in a GIS format was elaborated in year 2002 (Section 3.1.8) based on the Soil map of Luang Prabang Province scale 1:250.000 produced by the Soil Survey and Land Classification Center of NAFRI in the year 1995, on Topographic maps scale 1:100.000 produced in 1982 by the Department of Geography of Laos, on Aerial photographs scale 1:30.000 acquired in 1991, on a Geologic map of Lao PDR scale 1:1.000.000 and photogeological maps prepared in 1990 by the Department of Geology and Mines of Laos. The reports on how the soil map was elaborated do not give details about accuracy estimations.

The soil map was in digital form and its attribute table included the soil unit name but not the top soil properties. As explained in Section 4.2.3 it was necessary to transfer the properties from the laboratory results stored in Excel tables to the shape file using the soil name as identifier. This process may introduce errors if a polygon is assigned with soil properties that do not correspond to it.

In the evaluation of suitability the whole study area was included, but as mentioned in section 5.2, two soil units did not have data on cation exchange capacity and base saturation and were not evaluated under the fuzzy theory. For the initial suitability evaluation under the Boolean theory, the descriptive parameters given by NAFRI in the soils reports were used in order to maintain consistency within the experts' based classification. In the fuzzy evaluation, new fertility values were calculated using the laboratory results. This may induce slight differences in the inputs for both evaluations.

There is no rule of thumb about how to select the membership functions graphs or how to assign membership values. In this study the membership graphs were selected because the type of input data and because previous studies found acceptable results for similar parameters with certain curves. The use of different membership functions will introduce slightly variations to the final results. A more important role in the final suitability is caused by the weights given to the parameters.

Analytic Hierarchy Process (AHP) was employed to obtain the different weights for the fuzzy calculation (Section 4.5.1). AHP relies on pair wise comparisons between different parameters to assign importance levels. This process may be subjective and requires expertise knowledge and common sense. For this reason different land evaluators may assign different importance and different weights, which may result in different suitability maps.

For the calculation of fuzzy parameters and suitability, it was used the Raster Calculator tool from ArcGIS and the Spatial Analyst function. To create similarity matrices it was necessary to reclassify the results obtained using the Raster Calculator. During the whole process some cells information was lost, due perhaps to the algorithms employed by the program to make the reclassification. Even when these missing cells correspond to less than 0.5% of the study area they induce an error on the calculations.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

Land evaluation is not strict. Traditional methodologies which rely on Boolean logic require high accuracy and data detail that is difficult –if not impossible- to find in reality. Fuzzy logic can cope with low detail levels and allows for more flexibility in the suitability classification.

Land evaluators can benefit of the results from both Boolean and fuzzy theory models. Fuzzy methods require the selection of membership functions and weights that are not pre-established and require expertise. In Boolean classifications the suitability levels and the decisions about restrictions for land characteristics require expert knowledge as well. With a system such as ALES for the land evaluation the procedures to determine suitability can be straightforward, while the fuzzy methodology requires the determination of the weights and membership functions, which may not be so easy to define.

The main purpose of this study was the creation of suitability maps including non-physical parameters and the comparison with the native knowledge of suitability. This objective was fulfilled: the evaluation both crisp and fuzzy was done considering the information provided by the farmers and based on land qualities and land characteristics according to the FAO framework for land evaluation (1976).

The secondary objectives are evaluated in terms of the research questions posed in Chapter 1:

1. What areas are suitable and feasible for rubber and upland rice cultivation?

In Chapter 5 the suitability maps under the Boolean and the fuzzy classification systems were presented. According to the results, between 85% (Boolean) and 88% (fuzzy) of the total area is suitable for rubber, and between 88% (Boolean) and 89% (fuzzy) of the total area is suitable for upland rain fed rice, which is equivalent to an area between of 4,819.5 ha and 4,990 ha. In a final suitability protected areas such as forests have to be considered as not suitable. Because in this study the main purpose was the comparison between models those areas were included; this generates a difference of results when comparing with the farmers' suitability maps.

2. Is there any difference between FAO land suitability evaluation and the maps where fuzzy classification has been applied? Which results are more realistic?

The fuzzy classification was done based on land characteristics to assess land qualities. The overall suitability results are similar, the main difference are in the suitability classes. In the Boolean classification based on FAO framework for land evaluation (1976) few areas highly suitable were found, while with the fuzzy classification around 50% of the total study area was highly suitable for upland rice and 24% for rubber (Figure 5.4).

It is difficult to determine which results are closer to the real situation, but the inputs for both models were based on information collected from the farmers and on expertise knowledge about rubber and upland rice requirements. The results obtained for the current conditions seem to corroborate the information provided by the United Nations (2006) about the agricultural conditions in Lao PDR, where it is stated that there is a deficit in rice production for the country. Areas with high potential of suitability are not being used in all their capability due to the restrictions caused for the lack of infrastructure and the cultivation techniques. On the other hand, the results with the Boolean model seem to depict the current situation of the study area and the whole country: a deficit in rice production (UNDP, 2006). Using the fuzzy theory highly suitable areas were found for both land utilization types, and the comparison with the farmers shows a better correspondence.

3. Do the results obtained with FAO and fuzzy models correspond to the farmer's perception?

The farmers created their own soil units for the study area. To each one of these soil units they assigned a crop that can be cultivated. Their classification did not assign suitability classes. In this way, for the whole *Kum Ban* 37% of the total area was defined as suitable for upland rice and 14% as suitable for rubber. When comparing to the Boolean suitability maps made following the FAO framework, there is a low correspondence, mainly caused to the lack of highly suitable areas and the difference in suitability areas location. The fuzzy classification shows a better correlation with the farmers' suitability because it is less rigorous and more highly suitable areas were defined. Farmers did not include reserve areas and other places that may be suitable but are not currently used for rice or rubber due to tradition in use (e.g. paddy rice areas or forests). It seems that there are areas were the farmers prefer to cultivate upland rice independently of the potential yield they can obtain, perhaps due to tradition in use.

The additional questions included for the research allow providing additional information about the study:

1. What is the minimum input data required to obtain reasonable results?

It is difficult if not impossible to answer to this question because the field data and the fieldwork have not been detailed. Besides, the particular conditions of suitability and perception can vary from place to place. However, if this kind of work wants to be replicated for other areas of the country, it is required as main input a soils map with detailed laboratory results. Ideally this soils map has to contain all the soil properties required to assess fertility and to compare with the crop requirements. Lao PDR has a rough topography and slope plays an important role for suitability. Slope maps can be obtained on line from the USGS website. But the main input is the farmers' perception and knowledge. A land evaluation that does not consider the current conditions of the farmers may create an optimal suitability that may not coincide with the reality.

2. What is required to convert non-feasible cultivations into feasible ones?

Different parameters affect the suitability of upland rice and rubber in the study area. Physical parameters such as soil fertility can be improved using fertilizers but are not affordable for the farmers and may have consequences to the environment; other parameters that are important for suitability such as soil depth are difficult to control.

Non physical parameters such as accessibility or workability have an important influence in the feasibility and suitability of the crops. An area with low suitability due to its distance to the villages can be converted into a suitable and feasible one if the farmer can have its property close to the cultivation area, or constructing adequate roads besides tracking roads. These solutions require strong political and economical decisions that in the short term may not be available. In the ideal situation, new roads have to be constructed in the whole study area, and the villages arranged in such a way that the plots are accessible to the farmers. More technical support may be required to improve the yields and new cultivation techniques such as terracing and irrigation introduced to take advantage of the available land.

One main limitation for the farmers is the lack of knowledge on how to cultivate rubber. NAFRI and SIDA are creating workshops to teach about crop requirements and rubber production; these efforts have to be continued and extended.

NAFRI has made research in suitability for cash crops such as pineapple or banana. This type of crops, even when the land is suitable, may not be so feasible due to the distance from the farmers to their plots: These kinds of crops can be easily stolen and the distances to the villages may discourage farmers to cultivate them.

Another important factor for the farmers is the market tendencies, which they believe are quite unstable. If certain cash crops are going to be promoted, there is a need of promotion and extra support. Farmers may be willing to cultivate these crops if they feel there is a potential market.

3. Are land degradation aspects sufficiently considered?

Erosion was a parameter included in the fuzzy and the Boolean models. The assessment was done based on field observations. Farmers provided information about how they perceive the susceptibility of the land to erosion and these answers were considered as well. The weight given to erosion in the fuzzy model and in the decision trees for the Boolean model in ALES was low when compared to the other parameters considered. A better approach requires additional research and erosion models that were outside of the scope of this study.

6.2. Recommendations and further research

In this study fallow period was considered as an input given the importance given to it by the farmers. Fallow favours the soil recovery and farmers state that after some fallow years the yield production increases. Additional research can be done to determine the relationship between soil fertility and different fallow periods.

For the study area detailed information about soils perception has been obtained through workshops carried out by NAFRI in 2005 and published by Douangsavanh et al (2006). An additional step is the location of these soil units in maps for the Kum Ban. The soils map obtained from the farmers in this study is a first approach, but the maps presented a high level of generalization and the description name was translated into Lao, while the soils description obtained in the workshop was given in different dialects.

To make improvements in the cultivation techniques it is required collaborative effort between farmers and governmental organization. Investment may be required and a study of the limiting factors that constraint the potential suitability of the crops. The next step is to find alternatives to remove or minimize the effects of the limiting factors.

For future evaluations of land suitability in Lao PDR it is important to use the farmers' perception as an asset. If further comparisons between farmers' suitability perception and other suitability models are planned, it may be necessary to require the farmers to define suitability classes equivalent to the defined by the FAO framework for land evaluation (1976). The information provided by the farmers will allow having a realistic view of the main constraints that influence the feasibility of a crop.

7. REFERENCES

Burrough, P. A. (1989). "Fuzzy Mathematical Methods for Soil Survey and Land Evaluation." Journal of Soil Science **40**: 477-492.

Burrough, P. A. (1996). Natural objects with indeterminate boundaries. In Burrough, P.A. & Frank, A.U. (Eds). London, Taylor & Francis. p.p 3 - 28.

Cohen, J. (1960). "coefficient of agreement for nominal scales." Educational and Psychological Measurement **20** (1): 37-46.

de Bie, C. A. J. M. (2002). Novel Approaches to Use RS-Products for Mapping and Studying Agricultural Land Use Systems. ISPRS 2002 TC-VII : Commission VII, Working Group VII-2.1 on sustainable agriculture : International symposium on Resource and Environmental Monitoring, Hyderabad, India.

Douangsavanh, L., Manivong, V., Polthanee, A., Katawatin, R., Inoue, Y., (2006). "Indigenous Knowledge on Soil Classification of Ethnic Groups in Luang Prabang Province of the Lao PDR." Journal of Mountain Science **3**(No 3): 247-258.

Food and Agriculture Organization of the United Nations FAO (1976). A framework for land evaluation. Rome, FAO.

Food and Agriculture Organization of the United Nations FAO (1983). Guidelines : land evaluation for rainfed agriculture. Rome.

Groenemans, R., Van Ranst, E., Kerre, E., (1997). "Fuzzy relational calculus in land evaluation." Geoderma **77**: 283-298.

Hall, G. B., Wang, F., Subaryono, J., (1992). "Comparison of boolean and fuzzy classification methods in land suitability analysis by using geographical information systems." In: Environment and Planning A, 24(1992), pp. 497-516.

Klingebiel, A. A. and P. H. Montgomery (1966). Land - capability classification. Washington, D.C., U.S. Department of agriculture, soil conservation service.

Mahanty, S., Fox, J., Nurse, N., Stephen, P., and McLees, L., (2006). Hanging in the Balance: Equity in Community-Based Natural Resource Management in Asia, Bangkok: RECOFTC (Regional Community Forestry Training Center for Asia and the Pacific); Honolulu: East-West Center.

McBratney A. B. and Odeh I. O. A. (1997). "Application of fuzzy sets in soil science: Fuzzy logic, fuzzy measurements and fuzzy decisions." Geoderma **77**: 85-113.

Munsell Color Co. (1975). Munsell soil color charts. Baltimore, 1994.

National Agriculture & Forestry Research Institute NAFRI (2002). Reports On Soil & Land Suitability. Component Land Management. Vientiane, Lao PDR.

National Agriculture & Forestry Research Institute NAFRI (2005). Report on Rubber Suitability Zoning in the Central Development Zone, Na Mo District, Oudomsay Province. LSUAFRP Field Report No. 05/12. Vientiane, Lao PDR**:** 13.

National Agriculture and Forestry Research Institute NAFRI (2004). Report on Household Diagnostic Survey in Phonexay District, Luangprabang Province. LSUAFRP Field Report No. 2004/03. Vientiane, Lao PDR.

Nilsson E and Svensson AK (2005). Agro-Ecological Assessment of Phonxay District, Louang Phrabang Province, Lao PDR. A Minor Field Study. Geobiosphere Science Centre Physical Geography and Ecosystems Analysis. Lund, Sweden, Lund University**:** 114.

Olson, G. W. (1981). Soils and the environment. New York, Chapman & Hall.

Pease J. and Coughlin R. E. (2001). Land Evaluation and Site Assessment: A Guidebook for Rating Agricultural Lands

Rossiter, D. G. (1994). Lecture Notes: "Land Evaluation", Cornell University, College of Agriculture & Life Sciences, Department of Soil, Crop, & Atmospheric Sciences. Available: http://www.css.cornell.edu/landeval/le_notes/lecnot.htm. Accessed: November 15, 2006.

Rossiter, D. G. (2004). Technical Note: Statistical methods for accuracy assesment of classified thematic maps. Enschede, the Netherlands. Available: http://www.itc.nl/personal/rossiter/pubs/list.html#pubs_m_R. Accessed January 25, 2007, ITC**:** 46.

Rossiter, D. G., Wambeke V., (1997). Automated Land Evaluation System : ALES version 4.65 user's manual. Ithaca, Cornell University, Department of Soil, Crop & Atmospheric Sciences.

Saaty, T. L. and L. G. Vargas (2001). Models, methods, concepts, and applications of the analytic hierarchy process. Boston etc., Kluwer Academic.

Sánchez, P. A., Couto, W. & Buol, S.W (1982). "The fertility capability soil classification system: interpretation, applicability and modification." Geoderma **27**((4)): 283-309.

Schubert, P. (2004). Cultivation Potential in Hambantota District, Sri Lanka. A Minor Field Study. Geobiosphere Science Centre Physical Geography and Ecosystems Analysis. Lund, Sweden, Lund University**:** 68.

Sicat, R. S., Carranza, E. J. M. and Nidumolu, U. B., (2005). "Fuzzy modeling of farmers' knowledge for land suitability classification." Agricultural systems **83**(1).

Sys, C., van Ranst, E., Debaveye, J., (1991). Land evaluation : Part I. Principles in land evaluation and crop production calculations Part II. Methods in land evaluation Part III. Crop requirements. Brussels, General Administration for Development Cooperation.

Tang, H. J., Debavye, J., Ruan, D., Van Ranst, E., (1991). "Land suitability classification based on fuzzy sets theory." Pedologie **41**: 277-290.

U.S. Department of Agriculture, S. C. S. (1983). National agricultural land evaluation and site assessment handbook. Washington, DC.

U.S. Department of the Interior, B. o. R. (1951). Irrigated land use volume V : part 2 Land classification. Washington, D.C., United States Department of the Interior, Bureau of Reclamation Manual. U.S. Government Printing Office.

United Nations Capital Development Fund UNCDF (2002). Lao PDR - Fact Finding Mission Report. Available: http://www.uncdf.org/english/countries/laos/local_governance/other_project_related_reports/fact-finding_mission_mwinter1.pdf. Accessed December 12, 2006.**:** p.p. 37.

United Nations Development Programme UNDP (2001). Human Development Report 2001: Making New Technologies Work for Human Development. O. U. Press. New York. Available: http://www.doylefoundation.org/icsu/UNDP.htm Accessed Nov 5, 2006**:** 264.

United Nations Development Programme UNDP (2004). Human Development Report 2004. Cultural liberty in today's diverse world. New York. Available: http://hdr.undp.org/reports/global/2004/pdf/hdr04_complete.pdf Accessed Dec 4, 2006.**:** p.p. 285.

United Nations Development Programme UNDP (2006). Human Development Report 2006. Beyond scarcity: Power, poverty and the global water crisis. New York. Available: http://hdr.undp.org/hdr2006/pdfs/report/HDR06-complete.pdf. Accessed Dec 5, 2006.**:** p.p. 422.

United Nations Development Programme UNDP (2006). National Human Development Report 2006. International Trade and Human Development. Vientiane, Lao PDR**:** 218.

Van Ranst E. Tang H. Groenemans S. Sinthurahat S (1996). "Application of fuzzy logic to land suitability for rubber production in peninsular Thailand." Geoderma **70**: 1 -19.

Zadeh, L. A. (1965). "Fuzzy sets." Information and Control **8**: 338-353.

WWW References

GeographyIq. Laos Climate (2006) http://www.geographyiq.com/countries/la/Laos_climate_c.htm. Accessed January 30, 2007

National Statistics Centreof the Lao PDR (2007). Statistics in Lao PDR. http://www.nsc.gov.la/. Accessed January 25, 2007

Southtravels. Weather and Climate in Laos (2006). http://www.southtravels.com/asia/laos/weather.html. Accessed January 30, 2007.

United Nations Development Programme UNDP (2006). Human Development Report 2006, Human Development Indicators. Country Fact Sheets. http://hdr.undp.org/hdr2006/statistics/countries/country_fact_sheets/cty_fs_LAO.html, Accessed January 29, 2007

USGS (2006) Seamless Data Distribution System, Earth Resources Observation and Science (EROS)http://seamless.usgs.gov. Accessed September 22, 2007.

Wikipedia, the free encyclopaedia (2006). Laos. http://en.wikipedia.org/wiki/Lao_PDR, Accessed December 10 2006.

APPENDICES

Appendix 1. Format for interviews in Lao

ປະເທດລາວ ແຂວງຫຼວງພະບາງ ເມືອງໂພນໄຊ

ຄຳຖາມກ່ຽວກັບການຄຸ້ມຄອງ ແລະ ປະເພດການນຳໃຊ້ທີ່ດິນ,ແຮງງານ,ລາຍຮັບ,ຄວາມສາມາດໄປເຖິງ

ນຳເບີ້ຟອມສຳພາດ ________

ຜູ້ຖືກສຳພາດ ________ ທີ່ຕັ້ງຂອງບ້ານ ________ ວັນ,ເດືອນ,ປີ.............. ________

ປະເພດການນຳໃຊ້ດິນ	ເຈົ້ານຳໃຊ້ທີ່ດິນເຮັດຫຍັງ ________ ໃຊ້ນຳ້ຊົນລະປະທານບໍ່ ? ________ ໃຊ້ນ້ຳຝົນບໍ່ ? ________
ຂະໜາດຟາມ/ຕອນດິນ	ເຈົ້າມີຕອນດິນຫຼາຍປານໃດ ? ________
ຜົນຜະລິດ	ພືດຫຍັງທີ່ເຈົ້າປູກ ? ແປງທີ 1 ________ ແປງທີ 2 ________ ແປງທີ 3 ________ ແປງທີ 4 ________
ຍອດການລົງທຶນ	ເຈົ້າໃຊ້ເງິນຫຼາຍປານໃດລົງທຶນ ໃນຍາມເກັບກ່ຽວເທື່ອນຶ່ງ ? ໃຊ້ແກ່ນພັນຫຼາຍປານໃດ ກິໂລ ຕໍ່ຍາມເກັບກ່ຽວຄັ້ງນຶ່ງ ________
ແຮງງານຄົນ ເດືອນ /[illegible]	ມີຄົນຫຼາຍປານໃດເຮັດວຽກຢູ່ໃນຟາມ ________
ການນຳໃຊ້ເຄື່ອງມືຢູ່ໃນຟາມ	ເຈົ້າໃຊ້ແຮງງານສັດບໍ່ ? ໃຊ້ເຄື່ອງກົນຈັກບໍ່ ? ________
ປຸ໋ຍວິທະຍາສາດ	ເຈົ້າໃຊ້ປຸ໋ຍວິທະຍາສາດບໍ່ ? ຊະນິດໃດ ? ປຸ໋ຍຊີວະພາບ ________ ຢາປາບສັດຕູພືດ ________ ບໍ່ໄດ້ໃຊ້ຫຍັງ ________
ລະດັບຄວາມຮູ້ດ້ານເຕັກນິກ	ເຈົ້າໄດ້ຮັບການຝຶກອົບຮົມກ່ຽວກັບດ້ານກະສິກຳບໍ່ ? ________ ຖ້າຝຶກ,ຝຶກຈາກໃສ ? ________
ເຈົ້າຂອງທີ່ດິນ	ທີ່ດິນເປັນຂອງເຈົ້າບໍ່ ? ________ ເຈົ້າໄດ້ເຊົ່າທີ່ດິນບໍ່ ? ________
ລາຍຮັບ,ລາຍຮັບເພີ່ມປະມານ	ສະເລ່ຍລາຍຮັບຂອງເຈົ້າເທົ່າໃດຕໍ່ປີ ? ________ ເຈົ້າໄດ້ຮັບເງິນມາຈາກແຫຼ່ງອື່ນອີກບໍ່ ? ________ ແຫຼ່ງລາຍຮັບທີ່ເຈົ້າໄດ້ມາແມ່ນຫຍັງ ? ________ ໄດ້ຮັບຫຼາຍປານໃດ ? ________ ໃນແຕ່ລະພືດມີຈັກກິໂລ (ກະໂລ່ງ) ເຈົ້າຜະລິດຢູ່ໃນ ນຶ່ງລະດູ ? ________ ລະດູເກັບກ່ຽວໃນນຶ່ງປີມີຈັກເທື່ອ ? ________ ແຕ່ລະໆດູດົນປານໃດ ? ________
ການກັດເຊາະ	ທີ່ດິນ (ນ້ຳ) ສາມາດກັດເຊາະໄດ້ບໍ່ ? ________
ຄວາມສາມາດເຂົ້າໄປເຖິງໂດຍທາງ	ໃຊ້ເວລາຈັກຊົ່ວໂມງໄປເອົາຜົນຜະລິດ ໄປຂາຍຕະຫຼາດ ________ ໃຊ້ຫຍັງໃນການຂົນສົ່ງ ________ ສະພາບທັນທາງເປັນແນວໃດ ? ຍາກ ________ ທຳມະດາ ________ ດີ ________
ມີຫຍັງແດ່ທີ່ເຮັດໃຫ້ເຈົ້າຕັດສິນໃຈ	ມີຫຍັງແດ່ທີ່ເຮັດໃຫ້ເຈົ້າຕັດສິນໃຈປູກເຂົ້າ ? ມີຫຍັງແດ່ທີ່ເຮັດໃຫ້ເຈົ້າຕັດສິນໃຈຢາກປູກຢາງພາລາ ?
ໝາຍເຫດ	________

Appendix 2. Format for interviews in English

LAO PDR.
MANAGEMENT, LAND UTILIZATION TYPES, LABOUR, INCOME AND ACCESIBILITY

Interview ID:

Interviewed: ______ Location: ______ Village: ______ Date: ______

Land utilization type	What is the use of the land? ______ Is it irrigated? ______ Is it rainfed? ______
Produce	What cultivations are in your fields? ______
Capital Intensity (U$/ha)	How much money do you invest for one yield? How many Kg of seed to produce one yield? ______
Labour intensity man-months per ha	How many people work in the farm? ______
Farm power	Do you use animal force? Machinery? ______
Fertilizer	Do you use fertilizer? What kind? Organic ______ Chemical ______ None ______
*Level of technical knowledge	Is there any training for the farmers? ______
Farm size ha/household	How big is your farm? ______
Land tenure	Are you the land owner? ______
Incomes: value addeed (approx.) US$/ha	*What is the average income of the farmers? ______ Which crops do you cultivate? ______ How many Kg (Units) of each crop do you produce in one season? ______ How many yield seasons are in one year? ______ How long is each season? ______
Erosion	Is the land erodable? ______
Accessibility/Distance	How many hours you travel to take your products to the market? ______ Mean of transport? ______ How is the road condition? Poor ______ Regular ______ Good ______
*Questions to agriculture department/NAFRI	
Remarks	______

Appendix 3. Correspondence between Munsell Colour for soils and Farmer's colour description

Field Munsell Colour Description	Farmers Soil Description
Brown	Sandy loam
Brownish yellow	Red soil
Dark yellowish brown	Black soil
Dark yellowish brown	Black soil + beige stone (Hin kab)
Dark yellowish brown	Red soil
Dark yellowish brown	Sandy loam
Dark yellowish brown	Stone and Red soil
Dark yellowish brown	Yellow soil + beige stone (Hin kab)
Dark brown	Red soil
Dark brown	Sandy loam
Dark yellowish brow	Black and white soil (Din ki mon) + stone
Dusky red	Red and black soil
Dusky red	Sandy loam
Dusky red	Yellow soil + beige stone (Hin kab)
Light yellowish brown	Sandy loam
Red	Red soil
Red	Sandy loam
Reddish brown	Sandy loam
Reddish yellow	Sandy loam
Strong brown	Black soil lowland
Strong brown	Red and black soil
Strong brown	Red soil and stone (Hin kab)
Strong brown	Yellow soil + beige stone (Hin kab)
Very dark brown	Red and black soil
Yellowish brown	Red and black soil
Yellowish brown	Red soil
Yellowish brown	Red soil + beige stone (Hin kab)
Yellowish brown	Sandy loam
Yellowish red	Black soil lowland
Yellowish red	Sandy loam

Appendix 4. Correspondence between expert and farmers' classification

Farmers Soil Type	Experts' Soil Type	Experts' Soil Texture
Beige stone (Hin kab)	ACh	HC
Black and white soil (Din ki mon) + stone	ACh	CL
Black and white soil (Din ki mon) + stone	ACh	HC
Black soil	ACh	CL
Black soil	ACh	HC
Black soil	ACh	L
Black soil	LPe	R
Black soil	CMe	SL
Black soil + beige stone (Hin kab)	ACg	HC
Black soil + beige stone (Hin kab)	ACh	HC
Black soil + beige stone (Hin kab)	CMe	HC
Black soil lowland	ACh	HC
Black soil lowland	CMe	HC
Black soil upland	ACh	CL
Black soil upland	ACh	HC
Limestone	ACh	CL
Limestone	ACh	LC
Red and black soil	ACh	CL
Red and black soil	ACh	HC
Red and black soil	CMe	HC
Red and black soil	LPe	R
Red soil	ACh	CL
Red soil	CMe	CL
Red soil	ACg	HC
Red soil	ACh	HC
Red soil	CMe	HC
Red soil	LPe	R
Red soil	CMe	SL
Red soil + beige stone (Hin kab)	ACg	HC
Red soil + beige stone (Hin kab)	ACh	HC
Red soil + redish stone (Hin pha)	ACh	CL
Red soil + redish stone (Hin pha)	ACh	HC
Red soil + redish stone (Hin pha)	LPe	R
Red soil + yellow soil	ACg	HC
Red soil + yellow soil	ACh	HC
Red soil + yellow soil	CMe	HC
Red soil and stone (Hin kab)	ACh	CL
Red soil and stone (Hin kab)	ACh	HC
Red soil and stone (Hin kab)	ACh	L
Red soil and stone (Hin kab)	ACh	LC
Red soil and stone (Hin kab)	ACh	SL
Sandy loam	ACh	CL
Sandy loam	CMe	CL
Sandy loam	ACg	HC
Sandy loam	ACh	HC
Sandy loam	CMe	HC
Sandy loam	ACh	L
Sandy loam	ACh	LC
Sandy loam	LPe	R
Sandy loam	CMe	SL
Stone (Hin)	ACh	CL
Stone (Hin)	ACh	HC
Stone (Hin)	LPe	R
Stone (Hin kab)	ACh	CL
Stone (Hin kab)	ACh	HC
Stone (Hin kab)	LPe	R
Stone (Hin kab)	CMe	SL
Stone and Red soil	ACh	CL
Stone and Red soil	ACh	HC
Stone and Red soil	CMe	HC
Yellow soil + beige stone (Hin kab)	ACh	CL
Yellow soil + beige stone (Hin kab)	ACh	HC
Yellow soil + beige stone (Hin kab)	CMe	HC
Yellow soil + beige stone (Hin kab)	LPe	R

Appendix 5. Correspondence between depths and textures in field and on map

Field Munsell Colour Description	Measured depth (m)	MAP DEPTH (m)	Depth Difference (m)	Field Text. Code	MAP TEXTURE	VILLAGE
Dark yellowish brown	1.00	1.00	0.00	CL	HC	Thapo
Dark yellowish brown	1.00	1.00	0.00	CL	HC	Thapo
Dark brown	0.80	1.00	-0.20	S	HC	Thapo
Brownish yellow	0.50	1.00	-0.50	SIC	HC	Thapo
Red	0.80	0.97	-0.17	SIC	CL	Thapo
Strong brown	1.00	0.97	0.03	SIC	CL	Thapo
Strong brown	1.00	1.25	-0.25	SIC	HC	Thapo
Dark yellowish brown	1.00	1.25	-0.25	SIC	HC	Thapo
Yellowish brown	1.00	0.97	0.03	SIC	CL	Thapo
Dusky red	1.00	0.97	0.03	S	CL	Thapo
Reddish yellow	1.00	1.00	0.00	SC	HC	Thapo
Light yellowish brown	0.15	1.00	-0.85	LS	HC	Thapo
Dusky red	0.70	1.00	-0.30	SL	HC	Thapo
Dark yellowish brown	0.70	1.00	-0.30	L	HC	Thapo
Yellowish red	2.00	1.00	1.00	CL	HC	Thapo
Strong brown	0.30	1.00	-0.70	C	HC	Thapo
Yellowish brown	1.00	1.00	0.00	CL	HC	Thapo
Dusky red	0.20	1.00	-0.80	SC	HC	Thapo
Strong brown	1.00	0.81	0.19	SIC	CL	Nambo
Yellowish brown	0.40	0.30	0.10	SIC	CL	Nambo
Very dark brown	1.00	0.30	0.70	SIC	CL	Nambo
Yellowish brown	0.70	1.00	-0.30	CL	HC	Nambo
Dusky red	0.10	1.00	-0.90	L	HC	Nambo
Dark yellowish brown	0.15	0.97	-0.82	L	CL	Nambo
Yellowish brown	1.00	0.97	0.03	SIC	CL	Nambo
Dark yellowish bro	1.00	1.00	0.00	LS	HC	Nambo
Yellowish red	1.00	1.00	0.00	SIC	HC	Nambo
Dark yellowish brown	0.50	0.81	-0.31	SIC	CL	Huayman
Dark yellowish brown	1.00	1.25	-0.25	SL	SL	Huayman
Dusky red	0.50	0.10	0.40	SL	R	Huayman
Reddish brown	0.70	0.10	0.60	SL	R	Huayman
Dark yellowish brown	1.00	1.25	-0.25	SIC	SL	Huayman
Dark yellowish brown	1.00	1.25	-0.25	CL	CL	Huayman
Dark brown	0.30	0.10	0.20	CL	R	Huayman
Dark yellowish brown	0.07	0.80	-0.73	SL	CL	Huayman
Dark yellowish brown	1.00	0.80	0.20	SIC	CL	Huayman
Dark yellowish brown	0.40	0.81	-0.41	SIC	CL	Huayman
Yellowish red	3.00	1.25	1.75	SCL	L	Houaymaha-Pumpao
Strong brown	3.00	0.49	2.51	SCL	CL	Houaymaha-Pumpao
Red	1.00	1.00	0.00	LS	HC	Houaymaha-Pumpao
Dark yellowish brown	0.60	0.97	-0.37	SL	CL	Houaymaha-Pumpao
Dark yellowish brown	1.00	0.97	0.03	LS	CL	Houaymaha-Pumpao
Strong brown	1.00	0.97	0.03	LS	CL	Houaymaha-Pumpao
Dark yellowish brown	0.10	1.00	-0.90	LS	HC	Houaymaha-Pumpao
Brown	1.00	1.25	-0.25	SL	CL	Houaymaha-Pumpao

Appendix 6. Parameters for land characteristics employed in ALES model

Number	Code	SOILUNITS (MAP UNITS)	Texture (Top)	Depth	Fertility	Slope	Obs. Erosion	Fallow	Prox. Villages
1	A	ACg-D-HC-a(M)	HC	D	M	a	N	Vary	VC
2	B	ACh-D-CL-a(L)	CL	D	L	a	N	Vary	C
3	C	ACh-D-CL-b(M)	CL	D	M	b	N	Vary	F
4	D	ACh-D-CL-d(H)	CL	D	H	d	L	Vary	C
5	E	ACh-D-CL-d(M)	CL	D	M	d	L	Vary	F
6	F	ACh-D-HC-b(M)	HC	D	M	b	L	Vary	F
7	G	ACh-D-HC-c(H)	HC	D	H	c	L	Vary	VF
8	H	ACh-D-HC-c(M)	HC	D	M	c	N	Vary	VF
9	I	ACh-D-HC-d(M)	HC	D	M	d	L	Vary	VF
10	J	ACh-D-HC-e(M)	HC	D	M	e	L	Vary	F
11	K	ACh-D-L-b(M)	L	D	M	b	L	Vary	F
12	L	ACh-D-LC-c(M)	C	D	M	c	N	Vary	VF
13	M	ACh-M-CL-a(M)	CL	M	M	a	L	Vary	VF
14	N	ACh-M-CL-b(H)	CL	M	H	b	L	Vary	VF
15	O	ACh-M-CL-b(M)	CL	M	M	b	L	Vary	VF
16	P	ACh-M-CL-c(M)	CL	M	M	c	N	Vary	F
17	Q	ACh-M-SL-b(M)	SL	M	M	b	N	Vary	F
18	R	ACh-S-CL-c(M)	CL	S	M	c	N	Vary	C
19	S	ACh-S-CL-e(M)	CL	S	M	e	N	Vary	F
20	T	CMe-D-CL-a(M)	CL	D	M	a	N	Vary	F
21	U	CMe-D-HC-a(M)	HC	D	M	a	N	Vary	VC
22	V	CMe-D-SL-a(M)	SL	D	M	a	L	Vary	C
23	W	CMe-D-SL-b(M)	SL	D	M	b	L	Vary	VC
24	X	LPe-R-HC-e(M)	HC	R	M	e	H	Vary	F

Appendix 6. (Continuation)

Slope	%
a	0-5
b	5-10
c	10-20
d	20-50
e	50-100
f	100-200

Prox. To Villages		m
VC	Very close	0-500
C	Close	500-1000
F	Far	1000-2000
VF	Very far	>2000

Soil Depth		cm
R	Rock outcrop	0-30
S	Shallow	30-50
T	Thin	50-75
M	Moderate	75-100
D	Deep	

Soil Fertility	
N	None
L	Low
M	Medium
H	High

Soil Texture	
HC	Heavy Clay
CL	Clay Loam
C	Light Clay
L	Loam
SL	Sandy Loam

Observed Erosion	
N	None
L	Low
M	Medium
H	High

Fallow Period		Years
NF	No Fallow	0
YF	Young Fallow	1-2
MF	Medium Fallow	2-4
OF	Old Fallow	>4

Appendix 7. Decision Trees for ALES model

```
MLRR (Laos PDR Rubber and Rice Suitability Model) Decision Trees

DtId Type                            Where Used
--------------------------------------------------------------------------------
1    Severity Level                  urc,Accs
 > slp (slope)
   A (flat) [0-5 %]........ : 1 (accesible)
   B (undulating) [5-10 %] > rds (Proximity to villages)
      VC (Very close) [0-500 m : 1 (accesible)
      C (Close) [500-1000 m].. : 1 (accesible)
      F (Far) [1000-2000 m]... : 2 (low limitation)
      VF (Very far) [2000-5000 : 2 (low limitation)
      ?...................... : ?
   C (rolling) [10-20 %] > rds (Proximity to villages)
      VC (Very close) [0-500 m : 1 (accesible)
      C (Close) [500-1000 m].. : 2 (low limitation)
      F (Far) [1000-2000 m]... : 2 (low limitation)
      VF (Very far) [2000-5000 : 3 (limited access)
      ?...................... : ?
   D (hilly) [20-50 %] > rds (Proximity to villages)
      VC (Very close) [0-500 m : 2 (low limitation)
      C (Close) [500-1000 m].. : 2 (low limitation)
      F (Far) [1000-2000 m]... : 3 (limited access)
      VF (Very far) [2000-5000 : 3 (limited access)
      ?...................... : ?
   E (steeply dissected) [50-100 %] > rds (Proximity to villages)
      VC (Very close) [0-500 m : 2 (low limitation)
      C (Close) [500-1000 m].. : 3 (limited access)
      F (Far) [1000-2000 m]... : 3 (limited access)
      VF (Very far) [2000-5000 : 3 (limited access)
      ?...................... : ?
   F (mountainous) [100-200 %] > rds (Proximity to villages)
      VC (Very close) [0-500 m : 2 (low limitation)
      C (Close) [500-1000 m].. : 2 (low limitation)
      F (Far) [1000-2000 m]... : 3 (limited access)
      VF (Very far) [2000-5000 : 3 (limited access)
      ?...................... : ?
   ?...................... : ?

2    Severity Level                  urc,Eros
 > slp (slope)
   A (flat) [0-5 %] > ober (observed erosion)
      N (No erosion observed). : 1 (No erosion)
      L (Low erosion observed) : 2 (Low erosion)
      M (Moderated erosion obs : 2 (Low erosion)
      H (High erosion observed : 3 (Moderate erosion)
      ?...................... : ?
   B (undulating) [5-10 %] > ober (observed erosion)
      N (No erosion observed). : 1 (No erosion)
      L (Low erosion observed) : 2 (Low erosion)
      M (Moderated erosion obs : 2 (Low erosion)
      H (High erosion observed : 3 (Moderate erosion)
      ?...................... : ?
   C (rolling) [10-20 %] > ober (observed erosion)
      N (No erosion observed). : 1 (No erosion)
      L (Low erosion observed) : 2 (Low erosion)
      M (Moderated erosion obs : 2 (Low erosion)
      H (High erosion observed : 3 (Moderate erosion)
      ?...................... : ?
   D (hilly) [20-50 %] > ober (observed erosion)
      N (No erosion observed). : 1 (No erosion)
      L (Low erosion observed) : 2 (Low erosion)
      M (Moderated erosion obs : 3 (Moderate erosion)
      H (High erosion observed : 4 (High erosion ris)
      ?...................... : ?
   E (steeply dissected) [50-100 %] > ober (observed erosion)
      N (No erosion observed). : 1 (No erosion)
      L (Low erosion observed) : 2 (Low erosion)
      M (Moderated erosion obs : 3 (Moderate erosion)
      H (High erosion observed : 4 (High erosion ris)
      ?...................... : ?
```

```
   F (mountainous) [100-200 : =5
   ?...................... : ?

3    Severity Level                 urc,Fer
 > fer (Fertility)
   H (High fertility)...... : 1 (No limitation)
   M (Medium fertility) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 2 (Limited yield)
      YF (Young fallow) [1-2 y : 2 (Limited yield)
      MF (Medium fallow) [2-4  : 2 (Limited yield)
      OF (Old fallow) [4-7 yr] : 2 (Limited yield)
      ?...................... : ?
   L (Low fertility) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 3 (Low yield)
      YF (Young fallow) [1-2 y : 3 (Low yield)
      MF (Medium fallow) [2-4  : 2 (Limited yield)
      OF (Old fallow) [4-7 yr] : 2 (Limited yield)
      ?...................... : ?
   N (No fertility) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 4 (Impossible)
      YF (Young fallow) [1-2 y : 3 (Low yield)
      MF (Medium fallow) [2-4  : 3 (Low yield)
      OF (Old fallow) [4-7 yr] : 2 (Limited yield)
      ?...................... : ?
   ?...................... : ?

4    Severity Level                 urc,Mois
 > sdp (soil depth)
   R (rock outcrop) [0-30 c : 4 (Very low)
   S (surface) [30-50 cm] > stx (soil texture)
      HC (heavy clay)......... : 2 (Moderate)
      SL (sandy loam)......... : 3 (Low)
      CL (clay loam).......... : 1 (High)
      C (light clay)......... : 1 (High)
      L (loam)................ : =4
      ?...................... : ?
   T (thin) [50-75 cm] > stx (soil texture)
      HC (heavy clay)......... : 2 (Moderate)
      SL (sandy loam)......... : 3 (Low)
      CL (clay loam).......... : 1 (High)
      C (light clay)......... : 1 (High)
      L (loam)................ : =4
      ?...................... : ?
   M (moderately deep) [75-100 cm] > stx (soil texture)
      HC (heavy clay)......... : 2 (Moderate)
      SL (sandy loam)......... : 3 (Low)
      CL (clay loam).......... : 1 (High)
      C (light clay)......... : 1 (High)
      L (loam)................ : =4
      ?...................... : ?
   D (deep) [100-300 cm]... : =4
   ?...................... : ?

5    Severity Level                 urc,Root
 > sdp (soil depth)
   R (rock outcrop) [0-30 c : 3 (Limited rooting)
   S (surface) [30-50 cm].. : 2 (Slight limitatio)
   T (thin) [50-75 cm]..... : 1 (No limitation)
   M (moderately deep) [75- : =3
   D (deep) [100-300 cm]... : =3
   ?...................... : ?

6    Severity Level                 urc,Work
 > slp (slope)
   A (flat) [0-5 %] > sdp (soil depth)
      R (rock outcrop) [0-30 c : 4 (Impossible)
      S (surface) [30-50 cm] > stx (soil texture)
         HC (heavy clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 2 (Moderate)
            YF (Young fallow) [1-2 y : 2 (Moderate)
            MF (Medium fallow) [2-4  : 2 (Moderate)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         SL (sandy loam) > flw (Fallow period)
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      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 1 (Easy)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?....................... : ?
   CL (clay loam) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 2 (Moderate)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 3 (Difficult)
      ?....................... : ?
   C (light clay) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 1 (Easy)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?....................... : ?
   L (loam)................ : =4
   ?....................... : ?
T (thin) [50-75 cm] > stx (soil texture)
   HC (heavy clay) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 2 (Moderate)
      YF (Young fallow) [1-2 y : 2 (Moderate)
      MF (Medium fallow) [2-4  : 3 (Difficult)
      OF (Old fallow) [4-7 yr] : 3 (Difficult)
      ?....................... : ?
   SL (sandy loam) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 1 (Easy)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?....................... : ?
   CL (clay loam) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 2 (Moderate)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?....................... : ?
   C (light clay) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 1 (Easy)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?....................... : ?
   L (loam)................ : =4
   ?....................... : ?
M (moderately deep) [75-100 cm] > stx (soil texture)
   HC (heavy clay) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 2 (Moderate)
      YF (Young fallow) [1-2 y : 2 (Moderate)
      MF (Medium fallow) [2-4  : 3 (Difficult)
      OF (Old fallow) [4-7 yr] : 3 (Difficult)
      ?....................... : ?
   SL (sandy loam) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 1 (Easy)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?....................... : ?
   CL (clay loam) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 1 (Easy)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?....................... : ?
   C (light clay) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 1 (Easy)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?....................... : ?
   L (loam)................ : =4
   ?....................... : ?
D (deep) [100-300 cm] > stx (soil texture)
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         HC (heavy clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 2 (Moderate)
            YF (Young fallow) [1-2 y : 2 (Moderate)
            MF (Medium fallow) [2-4  : 3 (Difficult)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         SL (sandy loam) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 1 (Easy)
            YF (Young fallow) [1-2 y : 1 (Easy)
            MF (Medium fallow) [2-4  : 2 (Moderate)
            OF (Old fallow) [4-7 yr] : 2 (Moderate)
            ?...................... : ?
         CL (clay loam) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 1 (Easy)
            YF (Young fallow) [1-2 y : 1 (Easy)
            MF (Medium fallow) [2-4  : 2 (Moderate)
            OF (Old fallow) [4-7 yr] : 2 (Moderate)
            ?...................... : ?
         C (light clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 1 (Easy)
            YF (Young fallow) [1-2 y : 1 (Easy)
            MF (Medium fallow) [2-4  : 2 (Moderate)
            OF (Old fallow) [4-7 yr] : 2 (Moderate)
            ?...................... : ?
         L (loam)................ : =4
         ?...................... : ?
      ?...................... : ?
   B (undulating) [5-10 %] > sdp (soil depth)
      R (rock outcrop) [0-30 c : 4 (Impossible)
      S (surface) [30-50 cm] > stx (soil texture)
         HC (heavy clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 2 (Moderate)
            YF (Young fallow) [1-2 y : 2 (Moderate)
            MF (Medium fallow) [2-4  : 3 (Difficult)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
6    Severity Level                 urc,Work
(continued)
         SL (sandy loam) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 1 (Easy)
            YF (Young fallow) [1-2 y : 1 (Easy)
            MF (Medium fallow) [2-4  : 2 (Moderate)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         CL (clay loam) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 1 (Easy)
            YF (Young fallow) [1-2 y : 2 (Moderate)
            MF (Medium fallow) [2-4  : 2 (Moderate)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         C (light clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 1 (Easy)
            YF (Young fallow) [1-2 y : 1 (Easy)
            MF (Medium fallow) [2-4  : 2 (Moderate)
            OF (Old fallow) [4-7 yr] : 2 (Moderate)
            ?...................... : ?
         L (loam)................ : =4
         ?...................... : ?
      T (thin) [50-75 cm] > stx (soil texture)
         HC (heavy clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 2 (Moderate)
            YF (Young fallow) [1-2 y : 2 (Moderate)
            MF (Medium fallow) [2-4  : 3 (Difficult)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         SL (sandy loam) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 1 (Easy)
            YF (Young fallow) [1-2 y : 1 (Easy)
            MF (Medium fallow) [2-4  : 2 (Moderate)
            OF (Old fallow) [4-7 yr] : 2 (Moderate)
            ?...................... : ?
         CL (clay loam) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 1 (Easy)
            YF (Young fallow) [1-2 y : 2 (Moderate)
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         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 2 (Moderate)
         ?...................... : ?
      C (light clay) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 1 (Easy)
         YF (Young fallow) [1-2 y : 1 (Easy)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 2 (Moderate)
         ?...................... : ?
      L (loam)............... : =4
      ?...................... : ?
   M (moderately deep) [75-100 cm] > stx (soil texture)
      HC (heavy clay) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 2 (Moderate)
         MF (Medium fallow) [2-4  : 3 (Difficult)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      SL (sandy loam) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 1 (Easy)
         YF (Young fallow) [1-2 y : 1 (Easy)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 2 (Moderate)
         ?...................... : ?
      CL (clay loam) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 1 (Easy)
         YF (Young fallow) [1-2 y : 1 (Easy)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 2 (Moderate)
         ?...................... : ?
      C (light clay) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 1 (Easy)
         YF (Young fallow) [1-2 y : 1 (Easy)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 2 (Moderate)
         ?...................... : ?
      L (loam)............... : =4
      ?...................... : ?
   D (deep) [100-300 cm] > stx (soil texture)
      HC (heavy clay) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 2 (Moderate)
         MF (Medium fallow) [2-4  : 3 (Difficult)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      SL (sandy loam) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 1 (Easy)
         YF (Young fallow) [1-2 y : 1 (Easy)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 2 (Moderate)
         ?...................... : ?
      CL (clay loam) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 1 (Easy)
         YF (Young fallow) [1-2 y : 1 (Easy)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 2 (Moderate)
         ?...................... : ?
      C (light clay) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 1 (Easy)
         YF (Young fallow) [1-2 y : 1 (Easy)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 2 (Moderate)
         ?...................... : ?
      L (loam)............... : =4
      ?...................... : ?
   ?...................... : ?
C (rolling) [10-20 %] > sdp (soil depth)
   R (rock outcrop) [0-30 c : 4 (Impossible)
   S (surface) [30-50 cm] > stx (soil texture)
      HC (heavy clay) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 2 (Moderate)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
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      ?...................... : ?
   SL (sandy loam) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 2 (Moderate)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 3 (Difficult)
      ?...................... : ?
   CL (clay loam) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 2 (Moderate)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?...................... : ?
   C (light clay) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 1 (Easy)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?...................... : ?
   L (loam)............... : =4
   ?...................... : ?
T (thin) [50-75 cm] > stx (soil texture)
   HC (heavy clay) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 2 (Moderate)
      YF (Young fallow) [1-2 y : 2 (Moderate)
      MF (Medium fallow) [2-4  : 3 (Difficult)
      OF (Old fallow) [4-7 yr] : 3 (Difficult)
      ?...................... : ?
   SL (sandy loam) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 1 (Easy)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?...................... : ?
   CL (clay loam) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 2 (Moderate)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?...................... : ?
   C (light clay) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 1 (Easy)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?...................... : ?
   L (loam)............... : =4
   ?...................... : ?
M (moderately deep) [75-100 cm] > stx (soil texture)
   HC (heavy clay) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 2 (Moderate)
      YF (Young fallow) [1-2 y : 2 (Moderate)
      MF (Medium fallow) [2-4  : 3 (Difficult)
      OF (Old fallow) [4-7 yr] : 3 (Difficult)
      ?...................... : ?
   SL (sandy loam) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 1 (Easy)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?...................... : ?
   CL (clay loam) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 1 (Easy)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?...................... : ?
   C (light clay) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 1 (Easy)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?...................... : ?
   L (loam)............... : =4
```

```
         ?...................... : ?
      D (deep) [100-300 cm] > stx (soil texture)
         HC (heavy clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 2 (Moderate)
            YF (Young fallow) [1-2 y : 2 (Moderate)
            MF (Medium fallow) [2-4  : 3 (Difficult)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         SL (sandy loam) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 1 (Easy)
            YF (Young fallow) [1-2 y : 1 (Easy)
            MF (Medium fallow) [2-4  : 2 (Moderate)
            OF (Old fallow) [4-7 yr] : 2 (Moderate)
            ?...................... : ?
         CL (clay loam) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 1 (Easy)
            YF (Young fallow) [1-2 y : 1 (Easy)
            MF (Medium fallow) [2-4  : 2 (Moderate)
            OF (Old fallow) [4-7 yr] : 2 (Moderate)
            ?...................... : ?
         C (light clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 1 (Easy)
            YF (Young fallow) [1-2 y : 1 (Easy)
            MF (Medium fallow) [2-4  : 2 (Moderate)
            OF (Old fallow) [4-7 yr] : 2 (Moderate)
            ?...................... : ?
         L (loam)............... : =4
         ?...................... : ?
      ?...................... : ?
   D (hilly) [20-50 %] > sdp (soil depth)
      R (rock outcrop) [0-30 c : 4 (Impossible)
      S (surface) [30-50 cm] > stx (soil texture)
         HC (heavy clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 2 (Moderate)
            YF (Young fallow) [1-2 y : 3 (Difficult)
            MF (Medium fallow) [2-4  : 3 (Difficult)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         SL (sandy loam) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 2 (Moderate)
            YF (Young fallow) [1-2 y : 2 (Moderate)
            MF (Medium fallow) [2-4  : 2 (Moderate)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         CL (clay loam) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 2 (Moderate)
            YF (Young fallow) [1-2 y : 2 (Moderate)
            MF (Medium fallow) [2-4  : 2 (Moderate)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         C (light clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 1 (Easy)
            YF (Young fallow) [1-2 y : 2 (Moderate)
            MF (Medium fallow) [2-4  : 2 (Moderate)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         L (loam)............... : =4
         ?...................... : ?
      T (thin) [50-75 cm] > stx (soil texture)
         HC (heavy clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 2 (Moderate)
            YF (Young fallow) [1-2 y : 2 (Moderate)
            MF (Medium fallow) [2-4  : 3 (Difficult)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
MLRR (Laos PDR Rubber and Rice Suitability Model) Decision Trees

DtId Type                        Where Used

6    Severity Level              urc,Work
(continued)
         SL (sandy loam) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 1 (Easy)
            YF (Young fallow) [1-2 y : 2 (Moderate)
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         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      CL (clay loam) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 2 (Moderate)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      C (light clay) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 1 (Easy)
         YF (Young fallow) [1-2 y : 2 (Moderate)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      L (loam)................ : =4
      ?...................... : ?
   M (moderately deep) [75-100 cm] > stx (soil texture)
      HC (heavy clay) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 2 (Moderate)
         MF (Medium fallow) [2-4  : 3 (Difficult)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      SL (sandy loam) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 2 (Moderate)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      CL (clay loam) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 2 (Moderate)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      C (light clay) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 2 (Moderate)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      L (loam)................ : =4
      ?...................... : ?
   D (deep) [100-300 cm] > stx (soil texture)
      HC (heavy clay) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 2 (Moderate)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      SL (sandy loam) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 2 (Moderate)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      CL (clay loam) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 2 (Moderate)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      C (light clay) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 1 (Easy)
         YF (Young fallow) [1-2 y : 2 (Moderate)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      L (loam)................ : =4
      ?...................... : ?
   ?...................... : ?
E (steeply dissected) [50-100 %] > sdp (soil depth)
   R (rock outcrop) [0-30 c : 4 (Impossible)
```

```
S (surface) [30-50 cm] > stx (soil texture)
   HC (heavy clay) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 2 (Moderate)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 3 (Difficult)
      ?...................... : ?
   SL (sandy loam) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 1 (Easy)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?...................... : ?
   CL (clay loam) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 1 (Easy)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 3 (Difficult)
      ?...................... : ?
   C (light clay) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 1 (Easy)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 2 (Moderate)
      ?...................... : ?
   L (loam)................ : =4
   ?...................... : ?
T (thin) [50-75 cm] > stx (soil texture)
   HC (heavy clay) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 2 (Moderate)
      YF (Young fallow) [1-2 y : 2 (Moderate)
      MF (Medium fallow) [2-4  : 3 (Difficult)
      OF (Old fallow) [4-7 yr] : 3 (Difficult)
      ?...................... : ?
   SL (sandy loam) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 2 (Moderate)
      YF (Young fallow) [1-2 y : 3 (Difficult)
      MF (Medium fallow) [2-4  : 3 (Difficult)
      OF (Old fallow) [4-7 yr] : 3 (Difficult)
      ?...................... : ?
   CL (clay loam) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 2 (Moderate)
      MF (Medium fallow) [2-4  : 2 (Moderate)
      OF (Old fallow) [4-7 yr] : 3 (Difficult)
      ?...................... : ?
   C (light clay) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 1 (Easy)
      YF (Young fallow) [1-2 y : 2 (Moderate)
      MF (Medium fallow) [2-4  : 3 (Difficult)
      OF (Old fallow) [4-7 yr] : 3 (Difficult)
      ?...................... : ?
   L (loam)................ : =4
   ?...................... : ?
M (moderately deep) [75-100 cm] > stx (soil texture)
   HC (heavy clay) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 3 (Difficult)
      YF (Young fallow) [1-2 y : 3 (Difficult)
      MF (Medium fallow) [2-4  : 3 (Difficult)
      OF (Old fallow) [4-7 yr] : 3 (Difficult)
      ?...................... : ?
   SL (sandy loam) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 2 (Moderate)
      YF (Young fallow) [1-2 y : 3 (Difficult)
      MF (Medium fallow) [2-4  : 3 (Difficult)
      OF (Old fallow) [4-7 yr] : 3 (Difficult)
      ?...................... : ?
   CL (clay loam) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 3 (Difficult)
      YF (Young fallow) [1-2 y : 3 (Difficult)
      MF (Medium fallow) [2-4  : 3 (Difficult)
      OF (Old fallow) [4-7 yr] : 3 (Difficult)
      ?...................... : ?
   C (light clay) > flw (Fallow period)
```

```
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 3 (Difficult)
         MF (Medium fallow) [2-4  : 3 (Difficult)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      L (loam)................ : =4
      ?....................... : ?
   D (deep) [100-300 cm] > stx (soil texture)
      HC (heavy clay) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 3 (Difficult)
         YF (Young fallow) [1-2 y : 3 (Difficult)
         MF (Medium fallow) [2-4  : 3 (Difficult)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      SL (sandy loam) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 3 (Difficult)
         MF (Medium fallow) [2-4  : 3 (Difficult)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      CL (clay loam) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 3 (Difficult)
         MF (Medium fallow) [2-4  : 3 (Difficult)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      C (light clay) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 3 (Difficult)
         MF (Medium fallow) [2-4  : 3 (Difficult)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      L (loam)................ : =4
      ?....................... : ?
   ?....................... : ?
F (mountainous) [100-200 %] > sdp (soil depth)
   R (rock outcrop) [0-30 c : 4 (Impossible)
   S (surface) [30-50 cm] > stx (soil texture)
      HC (heavy clay) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 3 (Difficult)
         YF (Young fallow) [1-2 y : 3 (Difficult)
         MF (Medium fallow) [2-4  : 3 (Difficult)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      SL (sandy loam) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 3 (Difficult)
         MF (Medium fallow) [2-4  : 3 (Difficult)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      CL (clay loam) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 3 (Difficult)
         YF (Young fallow) [1-2 y : 3 (Difficult)
         MF (Medium fallow) [2-4  : 3 (Difficult)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      C (light clay) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 3 (Difficult)
         MF (Medium fallow) [2-4  : 3 (Difficult)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      L (loam)................ : =4
      ?....................... : ?
   T (thin) [50-75 cm] > stx (soil texture)
      HC (heavy clay) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 3 (Difficult)
         YF (Young fallow) [1-2 y : 3 (Difficult)
         MF (Medium fallow) [2-4  : 3 (Difficult)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      SL (sandy loam) > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 2 (Moderate)
         YF (Young fallow) [1-2 y : 3 (Difficult)
```

```
            MF (Medium fallow) [2-4  : 3 (Difficult)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         CL (clay loam) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 2 (Moderate)
            YF (Young fallow) [1-2 y : 3 (Difficult)
            MF (Medium fallow) [2-4  : 3 (Difficult)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         C (light clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 2 (Moderate)
            YF (Young fallow) [1-2 y : 3 (Difficult)
            MF (Medium fallow) [2-4  : 3 (Difficult)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         L (loam)................ : =4
         ?...................... : ?
      M (moderately deep) [75-100 cm] > stx (soil texture)
         HC (heavy clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 3 (Difficult)
            YF (Young fallow) [1-2 y : 3 (Difficult)
            MF (Medium fallow) [2-4  : 3 (Difficult)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
MLRR (Laos PDR Rubber and Rice Suitability Model) Decision Trees

DtId Type                          Where Used
--------------------------------------------------------------------------------
6    Severity Level                urc,Work
(continued)
         SL (sandy loam) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 2 (Moderate)
            YF (Young fallow) [1-2 y : 3 (Difficult)
            MF (Medium fallow) [2-4  : 3 (Difficult)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         CL (clay loam) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 3 (Difficult)
            YF (Young fallow) [1-2 y : 3 (Difficult)
            MF (Medium fallow) [2-4  : 3 (Difficult)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         C (light clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 2 (Moderate)
            YF (Young fallow) [1-2 y : 3 (Difficult)
            MF (Medium fallow) [2-4  : 3 (Difficult)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         L (loam)................ : =4
         ?...................... : ?
      D (deep) [100-300 cm] > stx (soil texture)
         HC (heavy clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 3 (Difficult)
            YF (Young fallow) [1-2 y : 3 (Difficult)
            MF (Medium fallow) [2-4  : 3 (Difficult)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         SL (sandy loam) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 2 (Moderate)
            YF (Young fallow) [1-2 y : 3 (Difficult)
            MF (Medium fallow) [2-4  : 3 (Difficult)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         CL (clay loam) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 2 (Moderate)
            YF (Young fallow) [1-2 y : 3 (Difficult)
            MF (Medium fallow) [2-4  : 3 (Difficult)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
            ?...................... : ?
         C (light clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 2 (Moderate)
            YF (Young fallow) [1-2 y : 3 (Difficult)
            MF (Medium fallow) [2-4  : 3 (Difficult)
            OF (Old fallow) [4-7 yr] : 3 (Difficult)
```

```
          ?...................... : ?
       L (loam)................ : =4
       ?...................... : ?
    ?...................... : ?
 ?...................... : ?

7    Severity Level                 rbr,Accs
 > slp (slope)
   A (flat) [0-5 %]........ : 1 (accesible)
   B (undulating) [5-10 %] > rds (Proximity to villages)
      VC (Very close) [0-500 m : 1 (accesible)
      C (Close) [500-1000 m].. : 1 (accesible)
      F (Far) [1000-2000 m]... : 1 (accesible)
      VF (Very far) [2000-5000 : 2 (low limitation)
      ?...................... : ?
   C (rolling) [10-20 %] > rds (Proximity to villages)
      VC (Very close) [0-500 m : 1 (accesible)
      C (Close) [500-1000 m].. : 1 (accesible)
      F (Far) [1000-2000 m]... : 2 (low limitation)
      VF (Very far) [2000-5000 : 3 (limited access)
      ?...................... : ?
   D (hilly) [20-50 %] > rds (Proximity to villages)
      VC (Very close) [0-500 m : 1 (accesible)
      C (Close) [500-1000 m].. : 1 (accesible)
      F (Far) [1000-2000 m]... : 2 (low limitation)
      VF (Very far) [2000-5000 : 3 (limited access)
      ?...................... : ?
   E (steeply dissected) [50-100 %] > rds (Proximity to villages)
      VC (Very close) [0-500 m : 1 (accesible)
      C (Close) [500-1000 m].. : 2 (low limitation)
      F (Far) [1000-2000 m]... : 3 (limited access)
      VF (Very far) [2000-5000 : 3 (limited access)
      ?...................... : ?
   F (mountainous) [100-200 %] > rds (Proximity to villages)
      VC (Very close) [0-500 m : 2 (low limitation)
      C (Close) [500-1000 m].. : 2 (low limitation)
      F (Far) [1000-2000 m]... : 3 (limited access)
      VF (Very far) [2000-5000 : 3 (limited access)
      ?...................... : ?
   ?...................... : ?

8    Severity Level                 rbr,Eros
 > slp (slope)
   A (flat) [0-5 %] > ober (observed erosion)
      N (No erosion observed). : 1 (No erosion)
      L (Low erosion observed) : 1 (No erosion)
      M (Moderated erosion obs : 2 (Slight erosion)
      H (High erosion observed : 3 (Moderate erosion)
      ?...................... : ?
   B (undulating) [5-10 %] > ober (observed erosion)
      N (No erosion observed). : 1 (No erosion)
      L (Low erosion observed) : 2 (Slight erosion)
      M (Moderated erosion obs : 2 (Slight erosion)
      H (High erosion observed : 3 (Moderate erosion)
      ?...................... : ?
   C (rolling) [10-20 %] > ober (observed erosion)
      N (No erosion observed). : 1 (No erosion)
      L (Low erosion observed) : 2 (Slight erosion)
      M (Moderated erosion obs : 2 (Slight erosion)
      H (High erosion observed : 3 (Moderate erosion)
      ?...................... : ?
   D (hilly) [20-50 %] > ober (observed erosion)
      N (No erosion observed). : 1 (No erosion)
      L (Low erosion observed) : 2 (Slight erosion)
      M (Moderated erosion obs : 3 (Moderate erosion)
      H (High erosion observed : 4 (High erosion ris)
      ?...................... : ?
   E (steeply dissected) [50-100 %] > ober (observed erosion)
      N (No erosion observed). : 1 (No erosion)
      L (Low erosion observed) : 2 (Slight erosion)
      M (Moderated erosion obs : 3 (Moderate erosion)
      H (High erosion observed : 4 (High erosion ris)
      ?...................... : ?
   F (mountainous) [100-200 %] > ober (observed erosion)
```

```
      N (No erosion observed). : 1 (No erosion)
      L (Low erosion observed) : 2 (Slight erosion)
      M (Moderated erosion obs : 3 (Moderate erosion)
      H (High erosion observed : 4 (High erosion ris)
      ?...................... : ?
   ?...................... : ?

9    Severity Level                rbr,Fer
 > fer (Fertility)
   H (High fertility)...... : 1 (No limitation)
   M (Medium fertility) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 2 (Limited yield)
      YF (Young fallow) [1-2 y : 2 (Limited yield)
      MF (Medium fallow) [2-4  : 1 (No limitation)
      OF (Old fallow) [4-7 yr] : 1 (No limitation)
      ?...................... : ?
   L (Low fertility) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 3 (Needs extra fall)
      YF (Young fallow) [1-2 y : 3 (Needs extra fall)
      MF (Medium fallow) [2-4  : 2 (Limited yield)
      OF (Old fallow) [4-7 yr] : 2 (Limited yield)
      ?...................... : ?
   N (No fertility) > flw (Fallow period)
      NF (No fallow) [0-1 yr]. : 4 (Impossible)
      YF (Young fallow) [1-2 y : 3 (Needs extra fall)
      MF (Medium fallow) [2-4  : 3 (Needs extra fall)
      OF (Old fallow) [4-7 yr] : 2 (Limited yield)
      ?...................... : ?
   ?...................... : ?

10   Severity Level                rbr,Mois
 > sdp (soil depth)
   R (rock outcrop) [0-30 c : 4 (Very low)
   S (surface) [30-50 cm] > stx (soil texture)
      HC (heavy clay)......... : 2 (Moderate)
      SL (sandy loam)......... : 3 (Low)
      CL (clay loam).......... : 1 (High)
      C (light clay)......... : 1 (High)
      L (loam)................ : =4
      ?...................... : ?
   T (thin) [50-75 cm] > stx (soil texture)
      HC (heavy clay)......... : 3 (Low)
      SL (sandy loam)......... : 3 (Low)
      CL (clay loam).......... : 2 (Moderate)
      C (light clay)......... : 1 (High)
      L (loam)................ : =4
      ?...................... : ?
   M (moderately deep) [75-100 cm] > stx (soil texture)
      HC (heavy clay)......... : 2 (Moderate)
      SL (sandy loam)......... : 3 (Low)
      CL (clay loam).......... : 1 (High)
      C (light clay)......... : 1 (High)
      L (loam)................ : =4
      ?...................... : ?
   D (deep) [100-300 cm] > stx (soil texture)
      HC (heavy clay)......... : 2 (Moderate)
      SL (sandy loam)......... : 2 (Moderate)
      CL (clay loam).......... : 1 (High)
      C (light clay)......... : 1 (High)
      L (loam)................ : =4
      ?...................... : ?
   ?...................... : ?

11   Severity Level                rbr,Root
 > sdp (soil depth)
   R (rock outcrop) [0-30 c : 4 (Impossible)
   S (surface) [30-50 cm].. : 4 (Impossible)
   T (thin) [50-75 cm]..... : 3 (Limited rooting)
   M (moderately deep) [75- : 3 (Limited rooting)
   D (deep) [100-300 cm]... : 1 (No limitation)
   ?...................... : ?

MLRR (Laos PDR Rubber and Rice Suitability Model)  Decision Trees
```

```
DtId Type                           Where Used
----------------------------------------------------------------------------------------------
12   Severity Level                 rbr,Work
 > slp (slope)
   A (flat) [0-5 %] > sdp (soil depth)
      R (rock outcrop) [0-30 c : 4 (Impossible)
      S (surface) [30-50 cm] > stx (soil texture)
         HC (heavy clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 1 (Easy)
            YF (Young fallow) [1-2 y : 1 (Easy)
            MF (Medium fallow) [2-4  : 1 (Easy)
            OF (Old fallow) [4-7 yr] : 2 (Moderate)
            ?...................... : ?
         SL (sandy loam)......... : =1
         CL (clay loam).......... : =1
         C (light clay)......... : =1
         L (loam)................ : =1
         ?...................... : ?
      T (thin) [50-75 cm] > stx (soil texture)
         HC (heavy clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 1 (Easy)
            YF (Young fallow) [1-2 y : 1 (Easy)
            MF (Medium fallow) [2-4  : 1 (Easy)
            OF (Old fallow) [4-7 yr] : 2 (Moderate)
            ?...................... : ?
         SL (sandy loam)......... : =1
         CL (clay loam).......... : =1
         C (light clay)......... : =1
         L (loam)................ : =1
         ?...................... : ?
      M (moderately deep) [75-100 cm] > stx (soil texture)
         HC (heavy clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 1 (Easy)
            YF (Young fallow) [1-2 y : 1 (Easy)
            MF (Medium fallow) [2-4  : 1 (Easy)
            OF (Old fallow) [4-7 yr] : 2 (Moderate)
            ?...................... : ?
         SL (sandy loam)......... : =1
         CL (clay loam).......... : =1
         C (light clay)......... : =1
         L (loam)................ : =1
         ?...................... : ?
      D (deep) [100-300 cm] > stx (soil texture)
         HC (heavy clay) > flw (Fallow period)
            NF (No fallow) [0-1 yr]. : 1 (Easy)
            YF (Young fallow) [1-2 y : 1 (Easy)
            MF (Medium fallow) [2-4  : 1 (Easy)
            OF (Old fallow) [4-7 yr] : 2 (Moderate)
            ?...................... : ?
         SL (sandy loam)......... : =1
         CL (clay loam).......... : =1
         C (light clay)......... : =1
         L (loam)................ : =1
         ?...................... : ?
      ?...................... : ?
   B (undulating) [5-10 %]. : =1
   C (rolling) [10-20 %]... : =1
   D (hilly) [20-50 %]..... : =1
   E (steeply dissected) [5 : =1
   F (mountainous) [100-200 %] > sdp (soil depth)
      R (rock outcrop) [0-30 c : 4 (Impossible)
      S (surface) [30-50 cm] > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 1 (Easy)
         YF (Young fallow) [1-2 y : 1 (Easy)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      T (thin) [50-75 cm] > flw (Fallow period)
         NF (No fallow) [0-1 yr]. : 1 (Easy)
         YF (Young fallow) [1-2 y : 1 (Easy)
         MF (Medium fallow) [2-4  : 2 (Moderate)
         OF (Old fallow) [4-7 yr] : 3 (Difficult)
         ?...................... : ?
      M (moderately deep) [75-100 cm] > flw (Fallow period)
```

```
        NF (No fallow) [0-1 yr]. : 1 (Easy)
        YF (Young fallow) [1-2 y : 1 (Easy)
        MF (Medium fallow) [2-4  : 2 (Moderate)
        OF (Old fallow) [4-7 yr] : 3 (Difficult)
        ?....................... : ?
     D (deep) [100-300 cm] > flw (Fallow period)
        NF (No fallow) [0-1 yr]. : 1 (Easy)
        YF (Young fallow) [1-2 y : 2 (Moderate)
        MF (Medium fallow) [2-4  : 2 (Moderate)
        OF (Old fallow) [4-7 yr] : 3 (Difficult)
        ?....................... : ?
     ?....................... : ?
  ?....................... : ?
```

Appendix 8. Fuzzy land characteristics and fuzzy suitability using ArcGIS Raster Calculator

For Fertility

Fuzzy logic for Organic Matter
Con([om_ras - om_ras] <= 2, 0, [om_ras - om_ras] > 2 & [om_ras - om_ras] < 4, ([om_ras - om_ras] - 2) / (4 - 2), 1)
Fuzzy logic for Cation Exchange Capacity
Con([cec_ras - cec_ras] <= 10, 0, [cec_ras - cec_ras] > 10 & [cec_ras - cec_ras] < 20, ([cec_ras - cec_ras] - 10) / (20 - 10), 1)
Fuzzy logic for Base Saturation
Con([BS_tot_ras - BS_tot_ras] <= 50, 0, [BS_tot_ras - BS_tot_ras] > 50 & [BS_tot_ras - BS_tot_ras] < 75, ([BS_tot_ras - BS_tot_ras] - 50) / (75 - 50), 1)
Fuzzy logic for Available Phosphorus
Con([p_avail - p_avail] <= 10, 0, [p_avail - p_avail] > 10 & [p_avail - p_avail] < 25, ([p_avail - p_avail] - 10) / (25 - 10), 1)
Fuzzy logic for Available Potassium
Con([k_avail - k_avail] <= 4, 0, [k_avail - k_avail] > 4 & [k_avail - k_avail] < 12, ([k_avail - k_avail] - 4) / (12 - 4), 1)
Fuzzy Fertility
[cec_fuzzy] * 0.46 + [om_fuzzy] * 0.14 + [BS_tot_fuzzy] * 0.3 + [k_avail_fuzzy] * 0.05 + [p_avail_fuzzy] * 0.05

For depth

Fuzzy depth rubber
Con([depth_ras] < 100, 1 / (1 + 400 * Sqr([depth_ras] - 100)), 1)

Fuzzy depth rice
Con([depth_ras] < 50, 1 / (1 + 400 * Sqr([depth_ras] - 50)), 1)

For slope

Con([slope] >= 150, 0, [slope] > 100 & [slope] < 150, 2 * Sqr((([slope] - 150) / (0 - 150))), [slope] < 100, 1 - 2 * Sqr(([slope] - 0) / (0 - 150)), 1)

Suitability for Rubber

Old Fallow

[dist_fuzzy - dist_fuzzy] * 0.06 * 0.1 + [depth_fz_rub] * 0.51 + [txt_fzy_rub] * 0.16 * 0.1 + [Slope_fuzzy] * 0.11 + [fertility_fuzzy] * 0.05 + [eroscls_fuzzy] * 0.01 * .1 + 0.8 * 0.10

Medium fallow
[dist_fuzzy - dist_fuzzy] * 0.06 * 0.1 + [depth_fz_rub] * 0.51 + [txt_fzy_rub] * 0.16 * 0.1 + [Slope_fuzzy] * 0.11 + [fertility_fuzzy] * 0.05 + [eroscls_fuzzy] * 0.01 * .1 + 0.7 * 0.10

No fallow
[dist_fuzzy - dist_fuzzy] * 0.06 * 0.1 + [depth_fz_rub] * 0.51 + [txt_fzy_rub] * 0.16 * 0.1 + [Slope_fuzzy] * 0.11 + [fertility_fuzzy] * 0.05 + [eroscls_fuzzy] * 0.01 * .1 + 0.6 * 0.1

Suitability for Rice

Medium Fallow
[dist_fuzzy - dist_fuzzy] * 0.04 * 0.1 + [dpth_fzy_rice] * 0.40 + [txt_fzy_rice] * 0.15 * 0.1 + [Slope_fuzzy] * 0.08 + [fertility_fuzzy] * 0.20 + [eroscls_fuzzy] * 0.01 * .1 + 0.6 * 0.10

Old Fallow
[dist_fuzzy - dist_fuzzy] * 0.04 * 0.1 + [dpth_fzy_rice] * 0.40 + [txt_fzy_rice] * 0.15 * 0.1 + [Slope_fuzzy] * 0.08 + [fertility_fuzzy] * 0.20 + [eroscls_fuzzy] * 0.01 * .1 + 0.7 * 0.10

No fallow
[dist_fuzzy - dist_fuzzy] * 0.04 * 0.1 + [dpth_fzy_rice] * 0.40 + [txt_fzy_rice] * 0.15 * 0.1 + [Slope_fuzzy] * 0.08 + [fertility_fuzzy] * 0.20 + [eroscls_fuzzy] * 0.01 * .1 + 0.4 * 0.1

Appendix 9. Pairwise comparison matrices to get weights for Upland Rice land qualities

Soil fertility		Fertility	Fallow	Average
	Fertility	1	2	0.67
	Fallow	1/2	1	0.33

Moisture Avail		Texture	Depth	Average
	Texture	1	1	0.5
	Depth	1	1	0.5

Erosion		Slope	Observed Eros	Average
	Slope	1	5	0.83
	Observed Eros	1/5	1	0.17

Workability		Slope	Texture	Fallow	depth	Average
	Slope	1	1/2	1/3	2	0.18
	Texture	2	1	2	2	0.38
	Fallow	3	1/2	1	2	0.30
	Depth	1/2	1/2	1/2	1	0.14

Accessibility		Slope	Proximity	Average
	Slope	1	1	0.5
	Proximity	1	1	0.5

Appendix 10. Pairwise comparison matrices to get weights for Rubber land qualities

Soil fertility		Fertility	Fallow	Average
	Fertility	1	1	0.5
	Fallow	1	1	0.5

Workability		Slope	Texture	Fallow	Depth	Average
	Slope	1	1	1/2	1	0.20
	Texture	1	1	1/2	1	0.20
	Fallow	2	2	1	1	0.35
	Depth	1	1	1	1	0.25

Moisture availability, erosion and accessibility as for upland rice

Appendix 11. Land characteristics weights for upland rice

Land quality	Land characteristic weight	
Soil Fertility	Fertility	0.20
	Fallow	0.10
Moisture Availability	Texture	0.12
	Depth	0.12
Rooting Conditions	Depth	0.27
Erosion	Slope	0.03
	Observed Erosion	0.01
Workability	Slope	0.01
	Texture	0.03
	Fallow	0.02
	Depth	0.01
Accessibility	Slope	0.04
	Proximity	0.04

Land characteristic final weight	
Fertility	0.20
Fallow	0.12
Texture	0.15
Depth	0.40
Slope	0.08
Obs. Eros	0.01
Proximity	0.04

Appendix 12. Land characteristics weights for rubber

Land quality	Land characteristic weight	
Soil Fertility	Fertility	0.05
	Fallow	0.05
Moisture Availability	Texture	0.14
	Depth	0.14
Rooting Conditions	Depth	0.34
Erosion	Slope	0.03
	Observed Erosion	0.01
Workability	Slope	0.02
	Texture	0.02
	Fallow	0.04
	Depth	0.03
Accessibility	Slope	0.06
	Proximity	0.06

Land characteristic final weight	
Fertility	0.05
Fallow	0.10
Texture	0.16
Depth	0.51
Slope	0.11
Obs. Eros	0.01
Proximity	0.06

Appendix 13. Similarity Matrixes for Boolean and Fuzzy suitability classes

Upland Rice

Table A13. 1. Boolean vs. Fuzzy Upland Rice No Fallow

		FUZZY SUITABILITY					
	Class	**0**	**1**	**2**	**3**	**4**	**Total**
ALES SUITABILITY	**1**	0	0	0	0	0	0
	2	163	859982	443552	57071	4041	1364809
	3	161	221176	350349	19330	10766	601782
	4	0	6434	7707	1074	246069	261284
	Total	324	1087592	801608	77475	260876	2227875
	Producer Accuracy	0.0	0.0	55.3	24.9	94.3	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
1	-	0.0	-	0	0	0.00
2	32.5	40.9	41.3	443552	1094041812872	-15.30
3	3.2	5.7	87.1	19330	46623060450	-2.82
4	94.2	94.3	0.2	246069	68162724784	93.57

Overall Accuracy	Kappa (%):	d	q	N
31.8	9.9	708951	1.209E+12	2227875

Table A13. 2. Boolean vs. Fuzzy Upland Rice Medium Fallow

		FUZZY SUITABILITY				
	Class	**1**	**2**	**3**	**4**	**Total**
ALES SUITABILITY	**1**	0	0	0	0	0
	2	880718	140621	56227	4041	1081607
	3	200764	653280	20174	0	874218
	4	6434	7707	1074	246069	261284
	Total	1087916	801608	77475	250110	2217109
	Producer Accuracy	0.0	17.5	26.0	98.4	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
1	-	0.0	-	0	0	0.00
2	13.0	14.9	25.9	140621	8.67025E+11	-61.00
3	2.3	4.2	91.1	20174	67730039550	-22.11
4	94.2	96.2	4.3	246069	65349741240	98.17

Overall Accuracy	Kappa (%)	d	q	N
18.4	-2.5	406864	1E+12	2217109

Table A13. 3. Boolean vs. Fuzzy Upland Rice Old Fallow

		FUZZY SUITABILITY				
	Class	1	2	3	4	Total
ALES SUITABILITY	1	0	0	0	0	0
	2	875030	140621	56227	3274	1075152
	3	206452	653280	20174	11533	891439
	4	6434	7707	1074	246069	261284
	Total	1087916	801608	77475	260876	2227875
	Producer Accuracy	0.0	17.5	26.0	94.3	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
1	-	0.0	-	0	0	0.00
2	13.1	15.0	25.4	140621	8.6185E+11	-59.37
3	2.3	4.2	91.3	20174	69064236525	-23.29
4	94.2	94.3	0.2	246069	68162724784	93.57

Overall Accuracy	Kappa (%):	d	q	N
18.3	-2.3	406864	9.991E+11	2227875

Rubber

Table A13. 4. Boolean vs. Fuzzy Rubber No Fallow

FUZZY SUITABILITY

	Class	1	2	3	4	Total
ALES SUITABILITY	1	5688	0	0	767	6455
	2	428770	410331	21228	1732	862061
	3	102398	396093	499117	23056	1020664
	4	5435	12923	73676	246661	338695
	Total	542291	819347	594021	272216	2227875
	Producer Accuracy	1.0	50.1	84.0	90.6	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
1	-	2.1	-	5688	3500488405	0.76
2	47.6	48.8	5.0	410331	7.06327E+11	18.57
3	48.9	61.8	41.8	499117	6.06296E+11	70.52
4	72.8	80.8	19.6	246661	92198198120	88.93

Overall Accuracy	Kappa (%):	d	q	N
52.1	33.2	1161797	1.41E+12	2227875

Table A13. 5. Boolean vs. Fuzzy Rubber Medium Fallow

FUZZY SUITABILITY

	Class	0	1	2	3	4	Total
ALES SUITABILITY	1	204	245398	203296	12992	792	462682
	2	120	221625	219510	8376	1707	451338
	3	0	69509	383618	498977	23056	975160
	4	0	5435	12923	73676	246661	338695
	Total	324	541967	819347	594021	272216	2227875
	Producer Accuracy		45.3	26.8	84.0	90.6	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
1	-	48.9	-	245398	2.50758E+11	30.94
2	48.6	34.5	-81.5	219510	3.69802E+11	8.19
3	51.2	63.6	39.1	498977	5.79266E+11	71.54
4	72.8	80.8	19.6	246661	92198198120	88.93

Overall Accuracy	Kappa (%):	d	q	N
54.3	38.3	1210546	1E+12	2227875

Table A13. 6. Boolean vs. Fuzzy Rubber Old Fallow

		FUZZY SUITABILITY					
	Class	**0**	**1**	**2**	**3**	**4**	**Total**
ALES SUITABILITY	**1**	0	0	0	0	0	0
	2	324	467023	422806	21368	2499	914020
	3	0	69509	383618	498977	23056	975160
	4	0	5435	12923	73676	246661	338695
	Total	324	541967	819347	594021	272216	2227875
	Producer Accuracy	0.0	0.0	51.6	84.0	90.6	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
1	-	0.0	-	0	0	0.00
2	46.3	48.8	10.4	422806	7.489E+11	17.93
3	51.2	63.6	39.1	498977	5.79266E+11	71.54
4	72.8	80.8	19.6	246661	92198198120	88.93

Overall Accuracy	Kappa (%):	d	q	N
52.4	33.4	1168444	1.42E+12	2227875

Appendix 14. Similarity Matrixes for Farmers and Fuzzy suitability classes. Comparison with all the classes.

Upland Rice

Table A14. 1. Farmers vs. Fuzzy Upland Rice No Fallow

FUZZY SUITABILITY	FARMERS SUITABILITY			
	Class	**0**	**1**	**Total**
	1	590321	497100	1087421
	2	596104	205471	801575
	3	76478	972	77450
	4	147698	113025	260723
	Total	1410601	816568	2227169
	Producer Accuracy	41.8	60.9	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
1	45.7	52.2	-	497100	8.87953E+11	23.55

Overall Accuracy	Kappa (%):	d	q	N
22.3	5.4	497100	8.88E+11	2227169

Table A14. 2. Farmers vs. Fuzzy Upland Rice Medium Fallow

FUZZY SUITABILITY	FARMERS SUITABILITY			
	Class	**0**	**1**	**Total**
	1	590645	497100	1087745
	2	596104	205471	801575
	3	76478	972	77450
	4	147698	113025	260723
	Total	1410925	816568	2227493
	Producer Accuracy	0.0	60.9	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
1	45.7	52.2	-	497100	8.88218E+11	23.54

Overall Accuracy	Kappa (%):	d	q	N
22.3	5.4	497100	8.882E+11	2227493

Table A14. 3. Farmers vs. Fuzzy Upland Rice Old Fallow

FARMERS SUITABILITY (columns) / FUZZY SUITABILITY (rows)

Class	0	1	Total
1	590645	497100	1087745
2	596104	205471	801575
3	76478	972	77450
4	147698	113025	260723
Total	1410925	816568	2227493
Producer Accuracy	41.9	60.9	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
1	45.7	52.2	-	497100	8.88218E+11	23.54

Overall Accuracy	Kappa (%):	d	q	N
22.3	5.4	497100	8.882E+11	2227493

Rubber

Table A14. 4. Farmers vs. Fuzzy Rubber No Fallow

FARMERS SUITABILITY (columns) / FUZZY SUITABILITY (rows)

Class	0	1	Total
1	484890	57338	542228
2	671746	147523	819269
3	540333	53600	593933
4	225643	46420	272063
Total	1922612	304881	2227493
Producer Accuracy	25.2	18.8	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
1	10.6	13.5	-	57338	1.65E+11	-7.32

Overall Accuracy	Kappa (%):	d	q	N
2.6	-0.8	57338	1.65315E+11	2227493

Table A14. 5. Farmers vs. Fuzzy Rubber Medium Fallow

FARMERS SUITABILITY

	Class	**0**	**1**	**Total**
FUZZY SUITABILITY	**0**	324	0	324
	1	484566	57338	541904
	2	671746	147523	819269
	3	540333	53600	593933
	4	225643	46420	272063
	Total	1922288	304881	2227169
	Producer Accuracy	0.0	18.8	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
0	-	0.0	-	0	15040080	0.00
1	10.6	13.5	-	57338	1.65E+11	-7.30

Overall Accuracy	Kappa (%):	d	q	N
2.6	-0.8	57338	1.65216E+11	2227493

Table A14. 6. Farmers vs. Fuzzy Rubber Old Fallow

FARMERS SUITABILITY

	Class	**0**	**1**	**Total**
FUZZY SUITABILITY	**1**	484566	57338	541904
	2	671746	147523	819269
	3	540333	53600	593933
	4	225643	46420	272063
	Total	1922288	304881	2227169
	Producer Accuracy	25.2	18.8	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
1	10.6	13.5	-	57338	1.65E+11	-7.30

Overall Accuracy	Kappa (%):	d	q	N
2.6	-0.8	57338	1.65216E+11	2227169

Appendix 15. Similarity Matrixes for Farmers and Fuzzy suitability classes. Aggregated comparison.

Upland Rice

Table A15. 1. Aggregated Farmers vs. Fuzzy. Upland Rice No fallow

FUZZY SUITABILITY	FARMERS SUITABILITY			
	Class	**0**	**1**	**Total**
	0	147698	113025	260723
	1	1262903	703543	1966446
	Total	1410601	816568	2227169
	Producer Accuracy	10.5	86.2	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
0	56.6	17.7	-441.0	147698	3.68E+11	-1.40
1	35.8	50.6	58.5	703543	1.61E+12	-18.24

Overall Accuracy	Kappa (%):	d	q	N
38.2	-2.6	851241	1.974E+12	2227169

Table A15. 2. Aggregated Farmers vs. Fuzzy. Upland Rice Medium fallow

FUZZY SUITABILITY	FARMERS SUITABILITY			
	Class	**0**	**1**	**Total**
	0	147698	113025	260723
	1	1263227	703543	1966770
	Total	1410925	816568	2227493
	Producer Accuracy	10.5	86.2	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
0	56.6	17.7	-441.2	147698	3.68E+11	-1.40
1	35.8	50.6	58.5	703543	1.61E+12	-18.25

Overall Accuracy	Kappa (%):	d	q	N
38.2	-2.6	851241	1.974E+12	2227493

Table A15. 3. Aggregated Farmers vs. Fuzzy. Upland Rice Old fallow

FARMERS SUITABILITY

FUZZY SUITABILITY	Class	0	1	Total
	0	147698	113025	260723
	1	1263227	703543	1966770
	Total	1410925	816568	2227493
	Producer Accuracy	10.5	86.2	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
0	56.6	17.7	-441.2	147698	3.68E+11	-1.40
1	35.8	50.6	58.5	703543	1.61E+12	-18.25

Overall Accuracy	Kappa (%):	d	q	N
38.2	-2.6	851241	1.974E+12	2227493

Rubber

Table A15. 4. Aggregated Farmers vs. Fuzzy. Rubber No fallow

FARMERS SUITABILITY

FUZZY SUITABILITY	Class	0	1	Total
	0	225643	46420	272063
	1	1696969	258461	1955430
	Total	1922612	304881	2227493
	Producer Accuracy	11.7	84.8	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
0	82.9	20.6	-606.7	225643	5.23E+11	-0.54
1	13.2	22.9	84.4	258461	5.96E+11	-24.66

Overall Accuracy	Kappa (%):	d	q	N
21.7	-1.1	484104	1.12E+12	2227493

Table A15. 5. Aggregated Farmers vs. Fuzzy. Rubber Medium fallow

FARMERS SUITABILITY (columns); FUZZY SUITABILITY (rows)

Class	0	1	Total
0	225967	46420	272387
1	1696645	258461	1955106
Total	1922612	304881	2227493
Producer Accuracy	11.8	84.8	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
0	83.0	20.6	-605.8	225967	5.24E+11	-0.54
1	13.2	22.9	84.4	258461	5.96E+11	-24.51

Overall Accuracy	Kappa (%):	d	q	N
21.7	-1.1	484428	1.12E+12	2227493

Table A15. 6. Aggregated Farmers vs. Fuzzy. Rubber Old fallow

FARMERS SUITABILITY (columns); FUZZY SUITABILITY (rows)

Class	0	1	Total
0	225643	46420	272063
1	1696645	258461	1955106
Total	1922288	304881	2227169
Producer Accuracy	11.7	84.8	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
0	82.9	20.6	-606.6	225643	5.23E+11	-0.54
1	13.2	22.9	84.4	258461	5.96E+11	-24.51

Overall Accuracy	Kappa (%):	d	q	N
21.7	-1.1	484104	1.12E+12	2227169

Appendix 16. Similarity Matrixes for Farmers and Boolean suitability classes

Upland Rice

Table A16. 1. Aggregated Farmers vs.Boolean. Rice no fallow

FARMERS SUITABILITY

ALES SUITABILITY	Class	0	1	Total
	0	151923	113548	265471
	1	1292812	709358	2002170
	Total	1444735	822906	2267641
	Producer Accuracy	10.5	86.2	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
0	57.2	17.8	-444.2	151923	3.84E+11	-1.35
1	35.4	50.2	58.9	709358	1.65E+12	-17.87

Overall Accuracy	Kappa (%):	d	q	N
38.0	-2.5	861281	2.031E+12	2267641

Table A16. 2. Aggregated Farmers vs.Boolean. Rice medium fallow

FARMERS SUITABILITY

ALES SUITABILITY	Class	0	1	Total
	0	151923	113548	265471
	1	1292812	709358	2002170
	Total	1444735	822906	2267641
	Producer Accuracy	10.5	86.2	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
0	57.2	17.8	-444.2	151923	3.84E+11	-1.35
1	35.4	50.2	58.9	709358	1.65E+12	-17.87

Overall Accuracy	Kappa (%):	d	q	N
38.0	-2.5	861281	2.031E+12	2267641

Table A16. 3. Aggregated Farmers vs.Boolean. Rice Old Fallow

ALES SUITABILITY	FARMERS SUITABILITY			
	Class	**0**	**1**	**Total**
	0	151923	113548	265471
	1	1292812	709358	2002170
	Total	1444735	822906	2267641
	Producer Accuracy	10.5	86.2	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
0	57.2	17.8	-444.2	151923	3.84E+11	-1.35
1	35.4	50.2	58.9	709358	1.65E+12	-17.87

Overall Accuracy	Kappa (%):	d	q	N
38.0	-2.5	861281	2.031E+12	2267641

Rubber

Table A16. 4. Aggregated Farmers vs.Boolean. No fallow

ALES SUITABILITY	FARMERS SUITABILITY			
	Class	**0**	**1**	**Total**
	0	288034	55292	343326
	1	1670444	253871	1924315
	Total	1958478	309163	2267641
	Producer Accuracy	14.7	82.1	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
0	83.9	25.0	-470.4	288034	6.72E+11	-0.51
1	13.2	22.7	83.9	253871	5.95E+11	-18.13

Overall Accuracy	Kappa (%):	d	q	N
23.9	-1.0	541905	1.267E+12	2267641

Table A16. 5. Aggregated Farmers vs.Boolean. Rubber Medium Fallow

FARMERS SUITABILITY

ALES SUITABILITY	Class	0	1	Total
	0	225643	46420	272063
	1	1696645	258461	1955106
	Total	1922288	304881	2227169
	Producer Accuracy	11.7	84.8	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
0	82.9	20.6	-606.6	225643	5.23E+11	-0.54
1	13.2	22.9	84.4	258461	5.96E+11	-24.64

Overall Accuracy	Kappa (%):	d	q	N
21.7	-1.1	484104	1.119E+12	2227169

Table A16. 6. Aggregated Farmers vs.Boolean. Rubber Old Fallow

FARMERS SUITABILITY

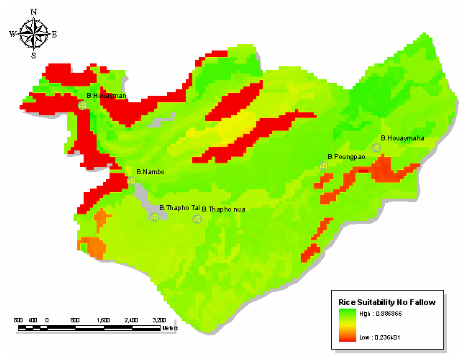
ALES SUITABILITY	Class	0	1	Total
	0	288034	55292	343326
	1	1670444	253871	1924315
	Total	1958478	309163	2267641
	Producer Accuracy	14.7	82.1	

Class	User Accuracy (%)	Mean Accuracy (%)	Areal Difference (%)	di	qi	Kappa per class (%)
0	83.9	25.0	-470.4	288034	6.72E+11	-0.51
1	13.2	22.7	83.9	253871	5.95E+11	-18.13

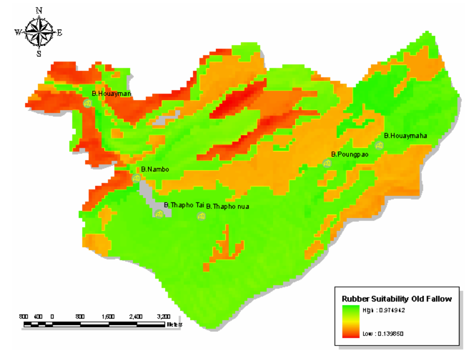
Overall Accuracy	Kappa (%):	d	q	N
23.9	-1.0	541905	1.267E+12	2267641

Appendix 17. Unclassified fuzzy-based results for upland rice and rubber

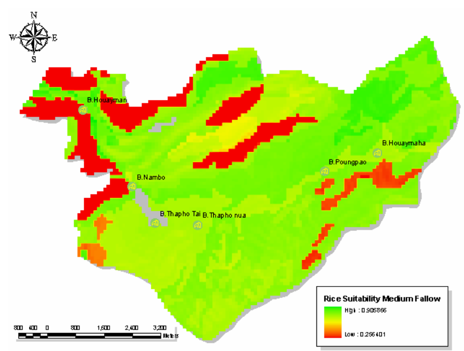
Rice suitability No fallow



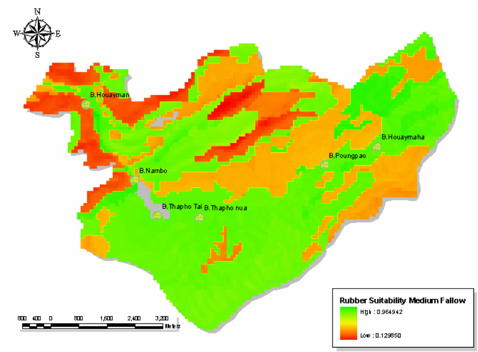
Rubber suitability, Old fallow



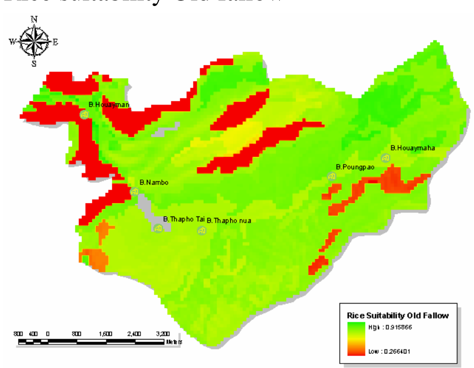
Rice suitability Medium fallow



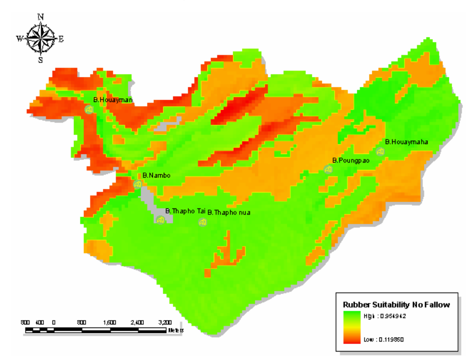
Rubber suitability, Medium fallow



Rice suitability Old fallow



Rubber suitability, No fallow



Appendix 18. Land suitability according to the farmers' perception